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U. Wittrock (Ed.)

Adaptive Optics for Industry and Medicine


With 283 Figures

Springer
Preface

The 4th International Workshop on Adaptive Optics for Industry and Medicine took place in Münster, Germany, from October 19 to October 24, 2003. The series of International Workshops on Adaptive Optics for Industry and Medicine began with the first workshop in Shatura/Russia in 1997, the second workshop took place in Durham/England in 1999, and the third workshop was held in Albuquerque/USA in 2001. The workshop series started out as a true grassroots movement and kept an informal spirit throughout all four workshops. Many personal friendships and scientific collaborations have been formed at these meetings.

This fourth workshop was supposed to be held in Beijing, China. However, the program committee decided in May 2003 to move the workshop to Münster due to the general perception that the SARS (Severe Acute Respiratory Syndrome) cases reported in China could lead to a large epidemic. Despite this rather short notice the workshop in Münster was attended by about 70 people. Incidentally, the workshop coincided with the 50th anniversary of adaptive optics, because it was October 1953 when Horace Babcock published his famous paper “The possibilities of compensating astronomical seeing” in the Publications of the Astronomical Society of the Pacific.

For years, adaptive optics has been synonymous for correction of atmospheric aberrations, but many more applications have emerged in recent years. Examples of fairly novel applications are imaging of the retina, confocal microscopy, laser resonators, dispersion compensation in ultrafast lasers, and free space optical communication. At the same time, significant progress has been made in reducing the cost of adaptive optics components such as deformable mirrors, driver electronics, or wavefront sensors. These factors are expected to lead to much more widespread applications of adaptive optics in the near future.

The workshops have never been associated with any of the big scientific societies. While this kept the cost for attendees low, it also meant that a lot of work had to be done by the local organizing committee. I’m very grateful to Agnes Frieling, Ivo Buske, Hagen Zimer, Hans Heuck, and Petra Welp for their great enthusiasm in organizing this workshop.
The attendees at the workshop in Münster voted to hold the 5th International Workshop on Adaptive Optics for Industry and Medicine in Beijing in 2005. I wish the organizers well in their undertakings and look forward to meeting many old and new friends in Beijing!

Münster, May 2005

Ulrich Wittrock
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Part I

Wavefront Correctors and Mirror Control
1 Micromachined Membrane Deformable Mirrors

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Summary. Development of adaptive optics, initiated 50 years ago with the article of Babcock [1], resulted in impressive technical and scientific results in military and astronomical applications. These results were obtained on a high price using custom-developed complex adaptive optical systems. Adaptive optics has a great potential to be applied in a range of optical systems, including imaging, ophthalmic, laser, optical communications and information processing. These systems are marketed widely and use relatively inexpensive parts with high performance. This article presents a fragmentary analysis of the current state and possible future development of inexpensive deformable mirrors for the industry and medicine. The analysis is mainly based on the results obtained by the author and his colleagues at the TU Delft and OKO Technologies during 1993–2003.

1.1 Design and Parameters

A Micromachined Membrane Deformable Mirror (MMDM) [2] consists of a thin stretched membrane suspended over an array of electrostatic electrodes. The membrane is fabricated by LPCVD deposition of a thin $\approx 0.5\,\mu m$ layer of tensile stressed silicon nitride $Si_3N_m$, followed by anisotropic etching of bulk silicon to release the membrane. Pure nitride membranes are sufficiently strong for mirrors with a diameter of up to 25 mm, larger membranes – up to 50 mm – can be fabricated by sandwiching a relatively thick – up to 10 $\mu m$ – layer of epitaxial polysilicon between two nitride layers.

In the simplest case the membrane is coated by a thin layer of metal – aluminum or gold – providing sufficiently reflective broadband coatings in the visible (Al) and infrared (gold) regions. In case a higher reflectivity is required (for instance for laser intracavity applications), the membrane can be coated with Cr/Ag composition followed by up to 12 dielectric layers, resulting in reflectivity of up to 99.8% in a narrow spectral region. Multilayer coated mirrors reported to work with laser loads of up to 550 W in a 5 mm circular beam at $\lambda = 1.06\,\mu m$. The typical parameters of a standard MMDM produced by OKO Technologies are shown in Table 1.1.

The initially flat membrane can be deformed only towards the electrostatic actuators because the electrostatic force can be only attractive. This limits...
Table 1.1. MMDM technical data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture shape</td>
<td>approximately circular</td>
</tr>
<tr>
<td>Mirror coating</td>
<td>Al, Au, HR ( R \approx 99.9% )</td>
</tr>
<tr>
<td>Aperture</td>
<td>diameter 15–50 mm</td>
</tr>
<tr>
<td>Number of electrodes</td>
<td>37–79</td>
</tr>
<tr>
<td>Control voltages ( V_c )</td>
<td>0...300 V</td>
</tr>
<tr>
<td>Initial rms deviation from plane</td>
<td>less than 0.3 ( \mu ) m</td>
</tr>
<tr>
<td>Main initial aberration</td>
<td>1 fringe at 630 nm</td>
</tr>
<tr>
<td>Frequency range</td>
<td>1000 Hz</td>
</tr>
<tr>
<td>Maximum deflection of the mirror center</td>
<td>9–30 ( \mu ) m</td>
</tr>
</tbody>
</table>

the possible optical figures of the MMDM to be always concave. Since most of the applications require both convex and concave operation of the mirror, the initial mirror figure is electrically biased to take a concave parabolic shape, median with respect to zero and maximum deflection. From this position, the mirror can correct both concave and convex aberrations with relation to the parabolically biased figure. The typical response time is \( \sim 1 \) ms, making the mirror suitable for real-time control of turbulence-induced aberrations.

1.2 Limitations

Technology of MMDM has certain limitations. The technology is suited for membranes with diameters in the range of 0.4–5.0 cm. It is difficult to fabricate larger or smaller mirrors. The effective number of electrodes is also limited. Electrostatic actuators can be easily integrated in very dense grids, resulting in small area per actuator. The maximum response per actuator is proportional to the actuator area. Practically it does not make sense to have actuators that produce maximum response of less than \( \lambda/4 \), which limits the maximum number of actuators to several hundreds for a 5 cm mirror. In practice, the mirror substrate should have voids, that are necessary for reduction of the air damping of the membrane movement. These voids should be uniformly spaced and they occupy a considerable area, even more reducing the possible number of uniformly spaced actuators.

The mirror membrane is fixed along its edges. To eliminate the influence of fixed boundary conditions, the light aperture should occupy approximately the central 50% of the mirror surface. For example, if a membrane mirror has an aperture of 15 mm, only the central area of 10 mm in diameter can be used for functional correction of wavefront aberrations. To ensure best spatial resolution, the array of electrostatic actuators is also placed under the central area of the membrane, occupying only about 60% of the membrane area.
The design of a micromachined deformable mirror allows deflection of the mirror surface only in the direction of the control electrodes, corresponding to a positive curvature of the mirror surface. To be able to correct an aberration that has both positive and negative curvature, the mirror surface should be pre-deformed to a concave spherical shape, having a weak positive optical power in the biased “zero” position. The surface displacement of the biased mirror surface limits the amplitude of the corrected aberration, moreover the correction amplitude and precision depends on the characteristic size of the aberration to be corrected.

The bias curvature $C_b = 1/R_b$, where $R_b$ is the radius of biased surface, should be equal to the half of the maximum achievable curvature $C_{\text{max}} = 1/R_{\text{max}} = 2/(R_b)$. The range of curvature control is limited by the curvature of the biased membrane. The shape of the membrane $s(x)$ – that is needed
to correct for a hypothetic harmonic aberration – can be described by a harmonic function with a period $T$ and amplitude $A$: $s(x) = A \sin(2\pi x / T)$ – for simplicity we consider a one-dimensional case. The curvature of the membrane $C(x) = 4\pi^2 A / T^2 \sin(2\pi x / T)$ is limited by the value of $4\pi^2 A / T^2$. This value (positive or negative) cannot exceed the absolute value of the bias curvature given by $|1/R_b|$. The amplitude of achievable harmonic deformation of the membrane mirror is given by

$$A_m = \frac{T^2}{4\pi^2 R_b}, \quad (1.1)$$

where $T$ defines the characteristic size of the aberration to be corrected. Finally the achievable $P-V$ correction amplitude in terms of wavefront deformation will be four times larger ($P-V$ amplitude of a harmonic function is two times larger than its amplitude, further the phase deformation equals to doubled mirror surface deformation), yielding for $P-V$ amplitude of wavefront correction:

$$A_{wf} = \frac{T^2}{\pi^2 R_b} = \frac{1}{\pi^2 f R_b}, \quad (1.2)$$

where $f$ is the spatial frequency of the surface deformation. For aberrations with a spatial period smaller than the mirror aperture, the membrane corrector represents a low-frequency filter, with a maximum amplitude of corrected aberration decreasing with aberration spatial frequency by 40 dB per decade or 12 dB per octave. For the typical values of our system $T = 1$ cm and $R_b = 4$ m – aberration over the whole aperture – the maximum amplitude of correction equals 2 $\mu$m while for a local aberration with $T = 5$ mm the maximum amplitude of correction is almost an order of magnitude lower and equals only 0.5 $\mu$m.

Equation 1.2 defines the maximum amplitude of the wavefront that can be corrected as a function of the aberration period $T$. $A$ is the maximum amplitude of a wavefront with a spatial period of $T_{\text{min}}$, that still can be corrected by the mirror. Wavefronts with larger amplitude and/or smaller periods cannot be corrected.

$$T_{\text{min}} = \pi \sqrt{R_b A}. \quad (1.3)$$

Assuming the mirror diameter is $D$ and we need at least 4 actuators to correct an aberration with a spatial period $T$, the total number of actuators providing correction with amplitude precision $A$ and period $T_{\text{min}}$

$$N = \frac{16D^2}{\pi^2 R_b A}. \quad (1.4)$$

For a deformable mirror with light aperture of $D = 10$ mm, $R_b = 5$ m and $A = 10^{-7}$ m we have $T_{\text{min}} \approx 2$ mm and $N \approx 300$. For comparison, the real device has only $N = 37$ actuators. For a mirror with $D = 35$ mm, $R_b = 20$ m and $A = 10^{-7}$ m we obtain $T_{\text{min}} \approx 4.5$ mm and $N \approx 1000$. 


As we made no assumption about the nature of the deformable mirror response, this analysis is valid in general for any curvature-limited deformable mirror device.

1.3 Applications

Since the technology of MMDM is based completely on inorganic materials, devices were demonstrated to work in vacuum at cryogenic temperatures down to $T = 78$ K [3], which makes them potentially suitable for space-based adaptive optics.

MMDM is reported to be successfully used for real-time correction of phase aberrations in laboratory and in a one meter telescope at Apache Point, New Mexico [4]. In particular, the Strehl ratio was improved in average from 0.08 to 0.48 for simulated turbulence in the laboratory, and from 0.04 to 0.1 in a 10-exposure field experiment with Altair image.

Small size, quick response, high density of actuators, smooth modal response and hysteresis-free operation make MMDM highly suitable for feed-forward correction using control approach based on a combination of optimization with program control. In the beginning, the voltage vector applied to the mirror electrodes is optimized to obtain the maximum of the appropriate quality parameter – brightness for laser systems, sharpness and image quality for imaging systems, pulse duration for ultrafast lasers. The optimization process can take up to several thousand iterations and usually results in significant improvement of the quality of the optical system. The control vector is written in the memory of the computer and can be recalled every time the control situation repeats.

Based on this approach, a wide field correction of scanning optical microscope was demonstrated in [5]. The scanning beam quality was individually optimized for each point in the field of view and the lookup table of MMDM control vectors was stored in the computer. In the operation mode, the scanning beam was corrected “on the fly” for each scan position, resulting in drastic improvement of the microscope resolution over the whole field.

Another example of the optimization approach combined with a lookup table is given in [6] – where the authors report on a $1 \times N$ optical switch with MMDM used to improve coupling efficiency in each switch channel of a fiber switch by pre-setting the mirror shape in accordance with the lookup table.

Optimization approach proved very efficient in numerous experiments with compression and optimization of ultrafast optical pulses. A special MMDM was developed for one-dimensional correction of phase aberrations along a single line. These devices are usually used in a stretcher of ultrafast laser to balance phase delays of spectral components. Optimization of the spectral phase resulted in efficient compression of femtosecond pulses and even in improvement of the efficiency of a EUV plasma source [7–9].
Fig. 1.2. Typical interferometric pattern of a 37-ch 15 mm MMDM: zero voltage applied, control byte 180 applied to all actuators, control byte 255 applied to all and to some actuators (left to right)

MMDMs were also successfully used for wavefront correction in terawatt lasers [10] and for intracavity control of high-power industrial lasers [11,12].

Finally, MMDM are suitable for real-time correction of the aberrations of the human eye, making possible “electronic spectacles” for real-time improvement of the visuoacuity [13].

Compactness, simplicity and high optical quality make MMDM the device of choice for a number of optical applications in the laser optics, imaging, optical testing and astronomy.

References

2 The Development and Optimisation of High Bandwidth Bimorph Deformable Mirrors

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   West Hanningfield Road, Chelmsford, England

Summary. Our first mirror designs were based on a standard bimorph construction and exhibited a resonant frequency of 1 kHz with a maximum stroke of ±5 µm. These devices were limited by the requirement to have a “dead space” between the inner active area and the mirror boundary. This was necessary to ensure that the requirements for both the stroke and the static boundary conditions at the edge of the mirror could be met simultaneously, but there was a significant penalty to pay in terms of bandwidth, which is inversely proportional to the square of the full mirror diameter. In a series of design iteration steps, we have created mounting arrangements that seek not only to reduce dead space, but also to improve ruggedness and temperature stability through the use of a repeatable and reliable assembly procedure. As a result, the most recently modeled mirrors display a resonance in excess of 5 kHz, combined with a maximum stroke in excess of ±10 µm. This has been achieved by virtually eliminating the “dead space” around the mirror. By careful thermal matching of the mirror and piezoelectric substrates, operation over a wide temperature range is possible. This paper will discuss the outcomes from the design study and present our initial experimental results for the most recently assembled mirror.

2.1 Introduction

The BAE SYSTEMS Advanced Technology Centre has been involved in a systems study to investigate the use of deformable mirrors to correct for distortions in atmospheric imaging and laser beam propagation. Typical applications include thermal imaging and laser remote sensing.

For correcting atmospheric distortions, the bandwidth required for the control system is typically 1 kHz. This means that the deformable mirror’s resonant frequency needs to be > 1 kHz. In terms of stroke, the correction of moderate turbulence (D/r₀ = 10, where D is the diameter of the aperture and r₀ is the coherence length), requires the capability to provide a movement of 0.5 µm (λ = 1 µm) over the mirror’s active surface. We have used these two basic parameters as the target requirements in the development of a number of prototype bimorph mirrors. 

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2.2 1st Iteration Flexure

2.2.1 Design and Fabrication

The first bimorph mirror fabricated was based on the standard scheme where a glass/PZT sandwich is supported rigidly around its edge. While this scheme is robust, the total substrate diameter is typically twice that of the required active area. Since the resonant frequency of this device is inversely proportional to the square of the mirror diameter, reducing the “dead” space at the periphery of the mirror was regarded as a prime objective. One way that this has been achieved in the past is to support the periphery of the mirror with an o-ring. This prevents any vertical displacement at the edge, but does enable a non-zero gradient. However, achieving an even pressure over the entire o-ring is difficult and requires careful adjustment of the clamping screws to avoid introducing mirror distortions. For this reason, we devised the 1st iteration flexure mount as an alternative mounting scheme. The flexures create a robust support which nevertheless enables a non-zero gradient at the mirror edge. This reduces the proportion of the mirror which is outside the main pupil.

Analytical modeling [1] was used to provide an initial estimate of the required substrate thickness. The trade off between the mirror stroke and resonant frequency is shown in Fig. 2.1.

The mirror was then drawn in Pro-Engineer, and transferred to Pro-Mechanica for finite element analysis. The electrode pattern chosen was based on the work carried out by Edric Mark Ellis in his thesis [1]. A photograph of the back of the mirror showing the flexures and electrode pattern, along with a picture of the fully assembled mirror is given in Fig. 2.2.

![Fig. 2.1. Analytical plot of mirror resonance and maximum displacement as a function of mirror substrate thickness](image)
### Table 2.1. Comparison of modelled and measured results

<table>
<thead>
<tr>
<th></th>
<th>Stroke (300 V pk–pk)</th>
<th>Resonant Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modelled(^a)</td>
<td>±7.3 (\mu)m</td>
<td>3.37 kHz</td>
</tr>
<tr>
<td>Final Mounted Mirror</td>
<td>±5 (\mu)m</td>
<td>2.7 kHz</td>
</tr>
<tr>
<td>% Achieved</td>
<td>62</td>
<td>80</td>
</tr>
</tbody>
</table>

\(^a\) The glue layer has not been taken into account in the modelled performance.

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**Fig. 2.2.** Photographs of the back of the mirror, showing the flexures and electrode pattern, and the fully assembled mirror

**Fig. 2.3.** Schematic of laser vibrometer test set-up

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### 2.2.2 Performance

A laser vibrometer (see Fig. 2.3 for schematic) was used to determine the resonant frequency and maximum stroke of the assembled device. A comparison of the modelled and measured results is given in Table 2.1.

From the table it can be seen that the measured resonant frequency is close to that predicted. The stroke achieved is only 60% of that predicted, but the model does not include the glue layer between the mirror substrate and PZT elements.

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### 2.3 2nd Iteration Flexure

#### 2.3.1 Design

While the 1st iteration flexure enabled a non-zero gradient at the mirror periphery, the unused portion of the mirror could be reduced even further if some vertical (piston) displacement were also possible. The 2nd iteration flexure is designed to provide this.
Fig. 2.4. Exaggerated 3D plots, and plots of mirror displacement for the 8 node and 16 node cases

Again, the mirror was drawn in Pro-Engineer, and transferred to Pro-Mechanica for finite element analysis, and the same 45 element electrode pattern was employed. This mirror was smaller than the 1st iteration design, and the substrate was fabricated from borosilicate glass. The PZT chosen matches the thermal expansion of the glass to within 0.25 ppm/°K. If you assume that no more than 10% of the maximum stroke should be used to compensate for thermal distortions, then the effective temperature range for the bimorph is ±64°C. This, in conjunction with suitable choice of epoxies and a PZT Curie temperature of > 200°C, gives the mirror a potential operating temperature range of between −40°C and +80°C.

Figure 2.4 shows the results of modelling the mirror, while Fig. 2.5 shows the bias voltages used to create the nodal patterns.