ACTIVE OPTICAL SYSTEMS

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Membrane Deformable Mirror Frequency Response

Author: **Justin D. Mansell, Ph.D.**
Active Optical Systems, LLC
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In this application note, we talk about the frequency response of our membrane deformable mirrors. We begin with an analysis of the first resonance of a membrane and then discuss the measured frequency response of our devices.

Membrane Resonance Theory

The theory governing the resonance frequencies of an ideal circular membrane under tension finds that the resonant frequencies are given by [1, 2, 3, 4],

$$f_n = C_n \frac{1}{D}\sqrt{\frac{T}{\rho}}$$

where f_n is the resonant frequency, C_n is a constant related to the Bessel functions, D is the membrane diameter, T is the membrane tension, and ρ is the membrane material area density. For the first mode, C_n is 0.76.

Due to the commercial off-the-shelf (COTS) nature of our membranes, we do not know the tension in the membranes during manufacture, but we can use the above equation to solve it for a given measured resonance frequency. We typically see first resonances in a membrane deformable mirror around 500 Hz, so for a polymer material density of ~500 kg/m^3, a thickness of 5 microns, and a diameter of 25 mm, we can estimate the membrane tension at 0.67 N/m.

Measuring Frequency Response

Figure 1 shows the experimental setup we used to measure the frequency response of the membrane deformable mirrors. Light from a HeNe laser was expanded with lenses L1 and L2 to fill the DM surface and then sampled with a beam splitter (BS) and lens L3 to illuminate a photodiode (PD). All the actuators were driven with the same voltage in the setup so the mirror surface took on a parabolic (focus) shape.

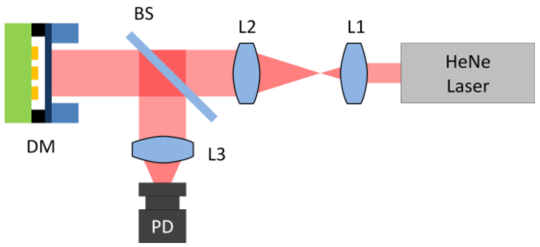


Figure 1 - Optical Setup for Frequency Response Testing

We initially proposed using an interferometer for determining the DM position as a function of applied signal, but the interferometer posed challenges in extracting the signal due to the non-linear response of the photodiode with DM position. Because the membrane DM is a curvature device and the intensity transport equation (ITE) is also a Laplacian, we decided to place an out-of-focus image of the

DM onto the photodiode which will give an approximately linear relationship between DM position and photodiode current.

We made measurements of several different membranes by exciting the DM with a sinusoidal signal and measuring the response on the photodiode. Figure 2 shows the frequency response of two 1” diameter membranes with different tensions. From this data we concluded that there are at least two phenomena acting together to produce this frequency response transfer function. On this plot we chose to use the electrical engineering convention of $20*\log_{10}(V)$ for the vertical axis. Before the first resonance of the mirror membrane, which is around 1 kHz, we see an approximate $1/f^{-0.25}$ reduction in frequency response. We believe that this is primarily due to air damping. After the resonance(s), the fall-off in frequency response fits well to an f^{-4} curve. Based on this fall-off rate, we believe that we are seeing two resonances in the data before the rapid fall-off.

Long-Term Drift Testing

In addition to the high-speed testing, we also did some long-term drift testing. In this case, we replaced L3 with a 5x reimaging telescope and replaced the photodiode in the experimental setup shown in Figure 1 with a our Shack-Hartmann Wavefront sensor based on a Marlin F131b camera. The mirror was biased to about half of its throw and the curvature was monitored over one evening into the morning. A frame was taken from the wavefront sensor every 30 seconds during the test. Figure 3(a) shows the fit to the focal power measured by the wavefront sensor in the x and y axes in the DM space (compensating for the 5x telescope). Figure 3(b) shows three coefficients of a Zernike decomposition of the wavefront measured by the wavefront sensor. In both plots we observe an oscillation at a very low frequency which we believe corresponds to the activation of the air conditioning units in the lab. The oscillation does not significantly affect the x and y tilts, but the tilt terms do drift as a function of time. The focal power is the same in magnitude in the x and y axes meaning that the shape drift is not astigmatic

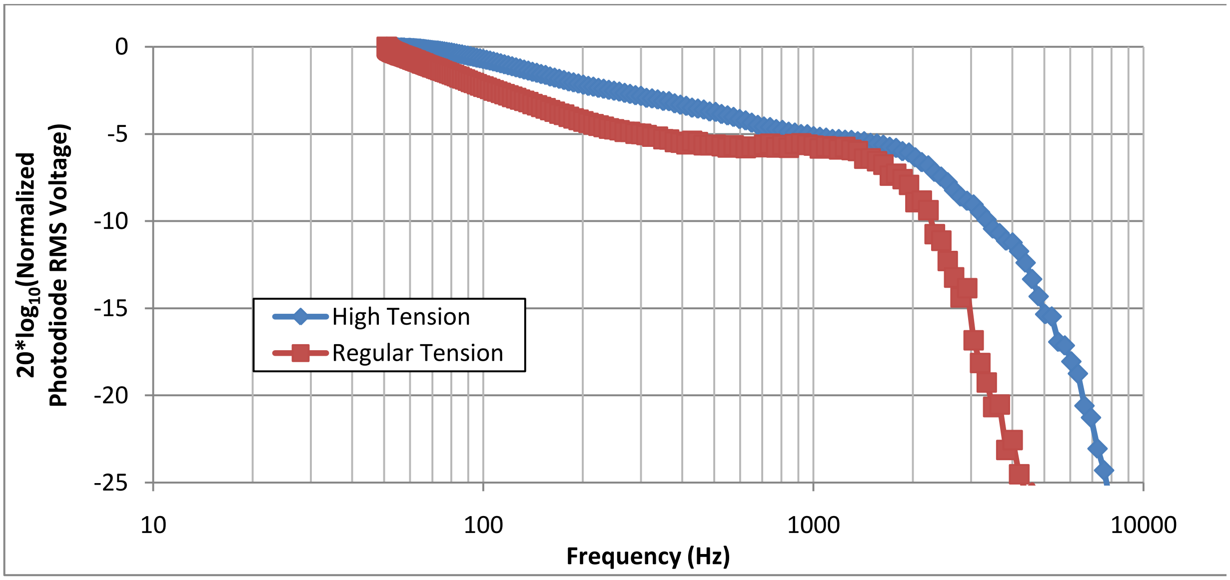


Figure 2 - Measured membrane DM response on a photodiode

(at 90-degrees), but is focus. The magnitude of the focus drift is ~0.01 diopters on the DM, which corresponds to about 100 m of curvature.

Comments on Environmental Factors

There are three environmental factors that contribute significantly to the performance of a membrane deformable mirror's frequency response: air damping, temperature, and humidity. Each of these will be discussed below.

Air Damping

The frequency response measurements showed a slight reduction in the performance of the mirror as a function of frequency well before a resonance occurs. There is evidence for this kind of damping in the literature [5]. In the future we intend to confirm this by running the same tests on the mirror in a reduced pressure environment.

Temperature

We are currently trying to establish the effect of temperature alone on the mirror membranes, but suspect that the long-term drift that we see in the membrane bias curvature over time is related to temperature changes.

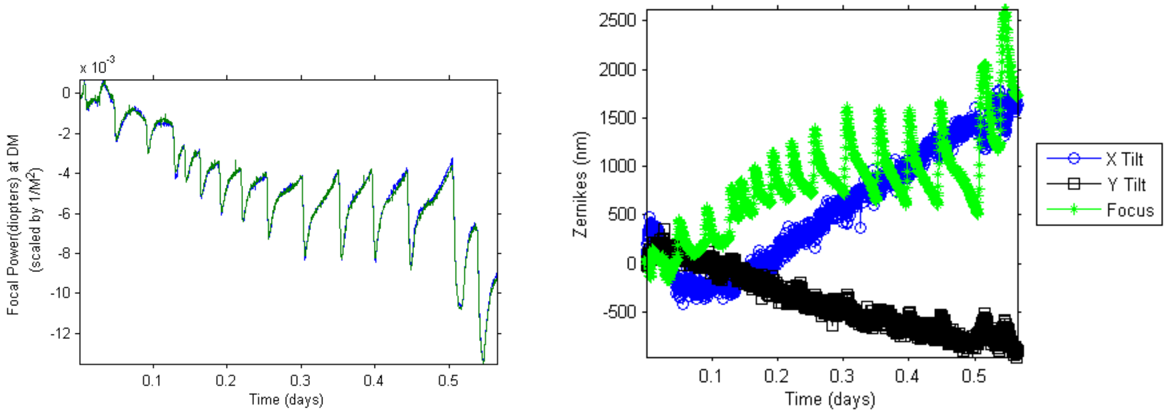
Humidity

Nitrocellulose membranes tend to take on water vapor from the air. This effect tends to reduce the tension in the membrane and thereby reduce its spring constant restoring force and the resonance frequencies.

There are several ways to mitigate the effects of humidity. One is to change the mirror membrane material. There are several literature sources that have used other materials for optical quality membranes. Another is to seal the membrane with a coating like a metal thin film on both surfaces. Finally, both air damping and humidity can be mitigated with a low-pressure vacuum chamber.

Conclusions

In this application note we have shown that



(a) (b)

Figure 3 - Results of long-term drift testing of a biased membrane deformable mirror showing the change in (a) the focal power in the two axes and (b) a decomposition of the shape into tilt and focus.

the membrane deformable mirrors have the ability to operate at a relatively high frequency, but are affected by air damping. During long-term operation, environmental factors like temperature and humidity affect the device performance, but in a typical laboratory environment, these changes correspond to a drift of approximately 100m of curvature during the course of 12 hours.

UPDATE: 9/7/2010

We have also now tested polyimide and nitrocellulose mirrors in varying humidity. Figure 4 below show these results. The polyimide membrane had much less humidity dependence than the nitrocellulose material. Also the high-tension polyimide had a much higher corner frequency.

References

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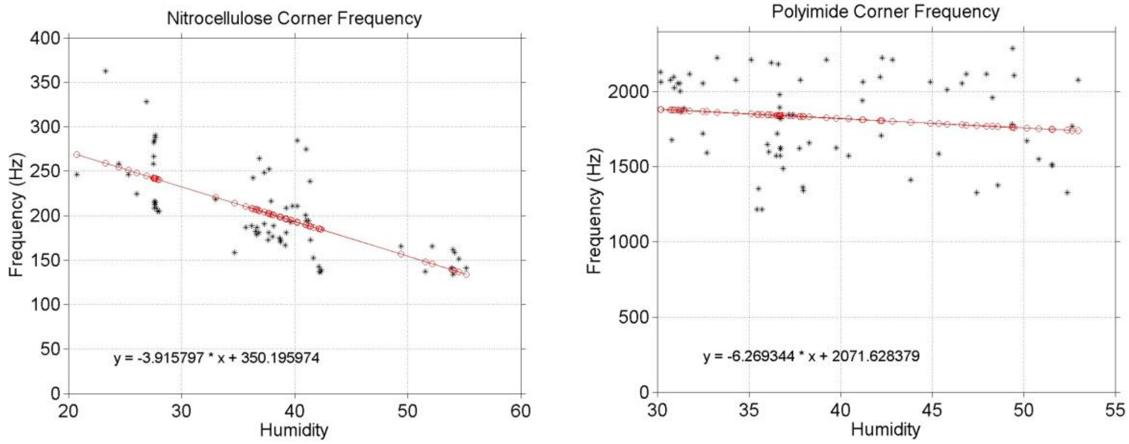

Figure 4 - Approximate 3-dB frequencies extracted from a polyimide membrane and a nitrocellulose membrane

Appendix A: Overlay of Visual Fits to the Measured Frequency Response

To help characterize the data we measured in the lab on the membrane DM response, we did two fits to the two sections of the curve. Before the resonance where we were affected by damping, we see a voltage response of $f^{-¼}$. After the resonance, the fall off fits nicely to $1/f^{-4}$.