Micromachined Deformable Mirrors for Adaptive Optics

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ABSTRACT

Recent progress on deformable mirror systems made at Boston University and Boston Micromachines Corporation is described. The mirror's optical, electrical, and mechanical performance characteristics are summarized, and the effects of air damping on performance are described. Two applications that have employed the μDM in laser communications and retinal imaging are introduced.

Keywords: Adaptive optics, deformable mirrors, wavefront control, MEMS

1. INTRODUCTION

Micromachined deformable mirror systems (μDMs) have been fabricated in the past year with optical quality rivaling that of the best conventional (macroscale) deformable mirrors. These μDMS are substantially faster, smaller, easier to control, and more economical than macroscale DMs [1,2]. They are currently the only commercially available zonally controlled microscale DMs. They have proven useful in commercial test beds for ophthalmic imaging, an application for which the μDM's small aperture is more suitable than the larger aperture of macroscale DMs [3].
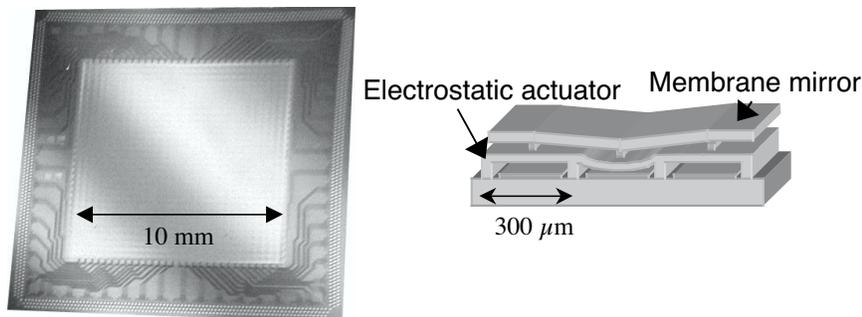

Figure 1: At left – photograph of a 1024 actuator deformable mirror chip, as fabricated. At right – schematic cross section of part of the device, showing electrostatic actuators and mirror membrane above a silicon substrate.

2. FABRICATION

These μDMs are fabricated using conventional silicon surface micromachining techniques, augmented by several processes (chemomechanical polishing, stress modification by ion bombardment, and low-stress evaporated gold coating) that have been developed specifically for optical microelectromechanical systems (MEMS) [4]. The thin film layers used in fabrication of the μDM are (from bottom to top):

1) A low-stress chemically vapor deposited (CVD) silicon nitride thin film. This 0.5μm thick layer provides electrical isolation between the substrate and the device.
2) A CVD silicon thin film. This 0.5μm thick structural layer is used for the fixed (bottom) actuator electrodes.

3) A CVD silicon dioxide thin film. This 5.0μm thick sacrificial layer is used to define the actuator gap.
4) A CVD silicon thin film. This 2.0μm thick structural layer is used for the bendable (top) actuator electrodes.
5) A CVD silicon dioxide thin film. This 2.5μm thick sacrificial layer is used as a spacer between the actuator and the mirror.
6) A CVD silicon thin film. This 3.0μm thick structural layer is used as the deformable mirror, and for attachment posts between the mirror and the actuators.
7) An evaporated gold thin film. This 50nm thick layer is used to improve mirror reflectivity.

Specifications for the mirror are detailed in Table 1.

Table 1: Performance characterisitics of μDMs

Clear aperture	3.3mm or 10 mm
Number of actuators	140 or 1024
Actuator configuration	12 x 12 or 32 x 32
Flatness (unpowered)	<30nm RMS
Reflectivity	>98% (@633nm)
Actuator spacing	300μm
Inter-actuator coupling	15%
Stroke	2μm
Hysteresis	0%
Drive voltage	220V max
Lifetime	>1B cycles @ 1/2 full stroke
Open loop bandwidth	DC-6.6kHz (in air)

3. DYNAMIC PERFORMANCE

The dynamic performance of the μDM is dominated by air damping effects. Without air damping, a mechanical bandwidth of approximately 70kHz would be expected, as compared to the 7kHz bandwidth measured in air.

Stiffness:

$$k = \frac{V^2 A \varepsilon_o}{2x(g-x)^2}$$

Natural Frequency:

$$f_n = \frac{1}{2\pi} \sqrt{\frac{k}{m_{mirror} + m_{actuator}}}$$
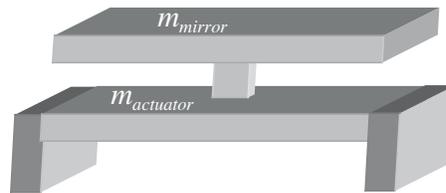
$$f_n \sim 70\ kHz$$

Figure 2: The undamped natural frequency of the mirror can be calculated using a simplified electromechanical analysis with the cantilever as a spring supporting the mirror and actuator masses. The observed actuation bandwidth of 7 kHz (3dB) is lower than the natural frequency because of the effects of air damping.

To probe the effects of air damping, a vacuum chamber was employed to regulate the μDM atmosphere during actuation. The chamber pressure was varied from 760 torr to 0.05 torr, and small amplitude signal frequency response was measured for the device motion in response to a swept-sine constant-amplitude driving signal. Though the actuator displacement varies nonlinearly with applied voltage, one can measure actuator bandwidth using small-amplitude (i.e. nearly linear) swept sine driving voltages.

The experimental setup is depicted in Figure 3. The measurement beam of a Polytec OFV 3001 vibrometer was focused on the mirror. Frequency response was measured by incrementally varying the drive frequency from 0.1Hz to 100kHz, while recording mirror displacement amplitude. Results are plotted in Figure 4:
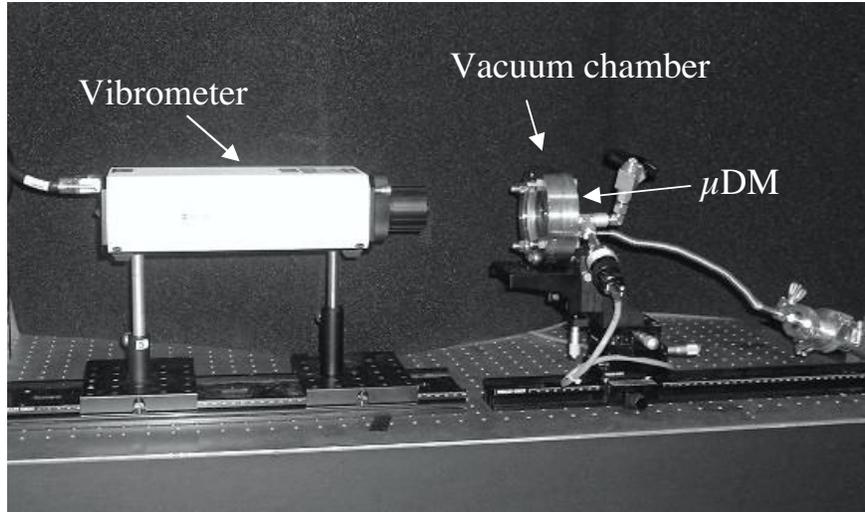

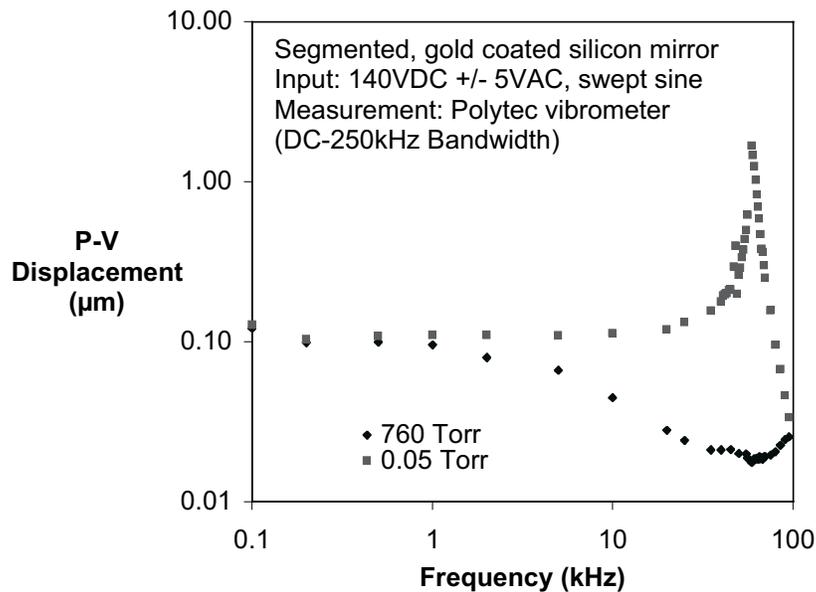Figure 3: Experimental test apparatus for measuring the effect of air damping on μDMs

Figure 4: Test results for air damping measurements. In atmospheric pressure (760 torr) the mirror motion is damped by air friction. In vacuum (0.05 torr), the expected 70kHz natural frequency is obtained, and the system is underdamped.

3. APPLICATION OF μDMS

The μDM device has recently been deployed in several adaptive optics applications. Two of particular interest are systems for laser communication and ophthalmic imaging. In laser communication, researchers at the Army Research Laboratory have used the μDM to compensate for horizontal-path atmospheric

turbulence in a 2.5km path between free-space infrared communication lasers [5]. They have closed the adaptive optics control loop at an iteration rate of approximately 10kHz, and have reduced bit error rates substantially through this close-loop compensation scheme. In ophthalmic imaging, a group at the Center for Visual Science at the University of Rochester has used the μDM to compensate for aberrations in the eye in a retinal imaging application [6]. A schematic of the system is shown in Figure 5. Notably, the performance of the μDM in this adaptive optics loop was comparable to that of a commercially available macroscale DM. However, the lower cost and smaller size of the μDM made it significantly more attractive than a macroscale mirror for this application.
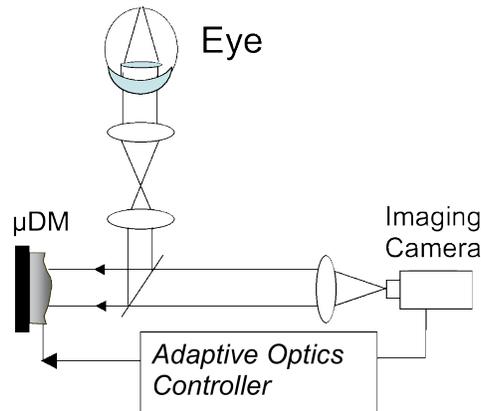

Figure 5: Schematic of adaptive optical system for retinal imaging. Using a fast, small silicon deformable mirror with ~100 actuators, one can improve retinal image resolution, allowing better diagnosis and treatment.

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