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VOLUME CONTROL MANIFOLD FOR MEMBRANE ADAPTIVE OPTICS (PREPRINT)

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Volume control manifold for membrane adaptive optics

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1. Abstract

An innovative adaptive optic concept is discussed that provides a dramatically improved dynamic bandwidth over existing approaches. This innovation is associated with membrane adaptive optics such as silicon nitride and polymer based films. This concept utilizes a volume control manifold that is co-located with the electrostatic actuators to dramatically improve total actuator force which in turn improves dynamic bandwidth and stroke. Presented is the result of a laboratory experiment showing time lapse images of a polymer film that is actuated by a single volume control actuator. An important constraint of the concept involves the depth of the air gap between the activated membrane and the backplate which includes both the electrostatic and volume control actuators. This depth is nominally less than 100 μm. At these depths, the viscosity of air becomes an important physical phenomenon.

2. Introduction

This Adaptive Optic (AO) concept referred to as a *Volume Control Manifold for Membrane Adaptive Optics* was enabled by products produced under the membrane mirror program at AFRL which developed the technology to manufacture large diameter (10-100 cm) optical quality polyimide based membrane films with dielectric coatings.[1,2] In this paper we review the stiffening and damping effect caused by the viscous nature of air trapped in the gap between the membrane and the actuation backplate. This phenomenon is used to dramatically improve the actuation force and overwhelmingly augment the force of a typical electrostatic actuator. Data from a single volume control actuator experiment will be shown, a summary of the relative force produced by a volume control actuator and an electrostatic actuator at a single design point, and the effects on the fundamental frequency of the membrane will also be discussed.

Since the late 1970's, when the earliest attempts at construction of adaptive mirrors using membranes were made by Grosso and Yellin,[3] it has been known that the air gap between membrane and backplate affects the dynamic behavior of the mirror. However, to the present day, this interaction does not appear to be well-understood, and to our knowledge has never been treated systematically with quantifiable results. By systematic and quantifiable, we mean an understanding of the mirror dynamics obtained by application of an appropriate theory. In fact, to our knowledge, the only attempt to explain the effects of the air gap occurred in the original paper by Grosso and Yellin[3] . A report generated by Wilkes [4] adds considerable details to this original paper.

Choosing the correct pressure within the air gap will result in a critically damped membrane where the air pressure is necessarily a small fraction of an atmosphere at the gap depths considered. The low air pressure reduces the load on the electrostatic actuators and improves stroke range. A critically damped device is an excellent choice for many designs, but the volume control manifold is better served by leaving the gap pressure at an atmosphere or even increasing the pressure above one atmosphere. Higher air pressure adds damping to the system, raising the fundamental frequency of the membrane and significantly enhances the performance of a volume control actuator which provides an overwhelming increase in the actuation force when compared to an electrostatic actuator. The following sections will describe the experiment, calculate the effects on the fundamental frequency using a single point design, compare electrostatic actuator force to the volume control actuator force, and present supporting laboratory data.

3. Hardware Description

The essential hardware used in the volume control experiment, consisting of a membrane, backplate, and a single PZT actuator, is shown in Figure 1. The gap depth is adjusted from 25-500 μm while the "nozzle" (drill thru) diameter is approximately 1 cm. The PZT is driven with a step function that expands the PZT by nominally 1 μm which in turn axially deforms the membrane by approximately one μm. The diagnostic snaps a series of interferograms that ultimately produce a sequence of surface deformations at 10 μs intervals. The backplate is 10 cm in diameter. There is no electrostatic actuator in the experiment.

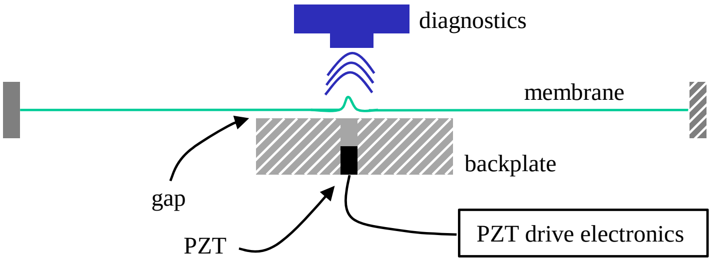

Figure 1. Experimental setup

The experimental membrane shown in Figure 2 is a 30 cm diameter, 5 μm thick polymer film (CP-1DE) manufactured by NeXolve Corporation (formerly SRS Technologies).[2] Note the spherical greenish pattern consisting of a number of concentric rings in the photo. This coloration is a result of the membrane producing Fizeau fringes from ambient light where the pattern is created by a slowing varying film thickness from center to edge.

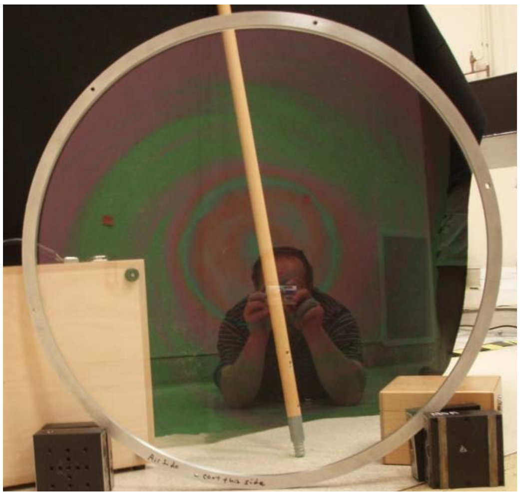

Figure 2. CP1-DE, 5 μm polyimide film used in experiment

4. Fundamental frequency

One atmosphere of pressure in the gap will stiffen the system and significantly dampen the membrane's "fundamental" modes of vibration; reducing the amplitude of these modes to indiscernible levels of deflection. Again, this fortunate circumstance is made possible by the viscous nature of the air within the gap. A comprehensive model of the gap fluid dynamics should account for the viscous nature of the gas both within the gap and on the surface of the membrane. The analysis is thus complicated as one must consider the coupling of the membrane dynamical equation to the Navier-

Stokes and mass conservation equations of viscous fluid dynamics. Further investigation is needed to gain a full understanding of the implications, but the initial results are promising.[4]

An indication of what might be expected of the resonant frequency when one particular limit is examined will help cast some light on the effect of the gap. We find that in the infinite-viscosity limit, the radial and circumferential velocity components of the gas must vanish, assuming no-slip boundary conditions at the surfaces of the enclosure.[5] The governing equations can then be solved for the resonant frequencies, which are given by the simple expression

$$f_{mn} = \frac{1}{2\pi}\omega_{mn} = \frac{1}{2\pi}\sqrt{\alpha_{mn}^2\left(\frac{T}{\gamma_0 a^2}\right) + \frac{p_0}{\gamma_0 l}}$$

where p_0 is the scale factor used to scale the pressure difference (taken to be standard atmospheric pressure), α_{mn} is the mth zero of the ordinary Bessel function J_n of order n. $T,\ \gamma_0,\ and\ a$ are properties associated with the membrane such as stress long the boundary, mass per area, and radius respectively while l is gap depth. The additional term $\frac{p_0}{\gamma_0 l}$ under the radical indicates a stiffening effect of the gas, and is equivalent to the gas acting purely as a spring. A significant amount of work is still required to sort out the impact of this and other results, and to put the entire design parameter space into perspective. This paper will not report on a parametric study of the design space but will present the results of a calculation assuming a representative membrane mirror device. This single point evaluation is accomplished at two pressures where $p_0 = 1$ Atm and $p_0 = 0$. These devices are frequently operated at a pressure that critically damps the membrane oscillations which is often a small percentage of an atmosphere, so choosing these two pressures will capture the essence of the relative magnitude of the two principle terms within the radical and demonstrate the stiffening effect of the trapped air within the gap. Choosing

$$\alpha_{mn} = \alpha_{11}, T = 125\frac{N}{M}, \gamma_0 = 10\frac{mg}{m}, a \quad = 5\ cm, l = 100\ um, p_0 = (0,1\ atm)$$

we calculate;

$$f_{11}(p_0 = 0) = 1.35\ kHz \ll f_{11}(p_0 = atm) = 50\ kHz.$$

The resonant frequency increased well over an order of magnitude and this of course allows one to increase the control bandwidth. At one atmosphere of pressure the first term under the radical that is normally associated with the membrane mode of vibrations plays almost no role in the calculation.

Actuator force

The previous section shows the possibility of a substantial increase in control bandwidth but the electrostatic actuator force does not allow operation at the higher frequencies required when the gap pressure is at an atmosphere. We now compare the actuation force (pressure) of the electrostatic actuator to that of the volume control actuator. This approximation assumes no lateral movement of the air within the gap, so the calculation will prove to be slightly optimistic. Comparing the pressure from a 100 volt electrostatic actuator and a volume of air changed by 0.1% will produce a pressure more than an order of magnitude greater than the electrostatic counterpart. The force of the volume control actuator dominates and, since the volume actuator is not opposed by the trapped air within the gap (the air is removed by the volume actuator) like the electrostatic actuator, the actuation force should allow for a much larger stroke at higher frequencies. Note that the volume control actuator must work in unison with an electrostatic actuator because volume control by itself will eventually equilibrate to some undesirable shape. Using electrostatics in conjunction with volume control, however, should allow the shape formed by volume control to be maintained.

Experimental data

Figure 3 shows a set of time-laps images of the membrane's surface. The images are spaced at 10 μs intervals with P-V amplitudes proportional to the diagnostic wavelength of 633 nm. The total length of the x and y axes are 2.5 cm long.

This data supports the claim that the control bandwidth could be substantial but a tremendous amount of research would be required to determine and quantify how such an idea would work in unison with a set of electrostatic actuators. One might imagine the volume control actuator quickly moving the membrane to a new shape like the shape shown in frame 3 (P-V=.68) of Figure 3, for example, and then electro-statically freeze that shape, never allowing the remaining sequence (dynamics) to occur. One would also want to learn more about the extent of spatial control. Here the centimeter diameter actuator is large and the gap is 225 μm which is much thicker than the 50 μm to 100 μm one might expect in a typical system. Much must be done to explore the range of spatial control.

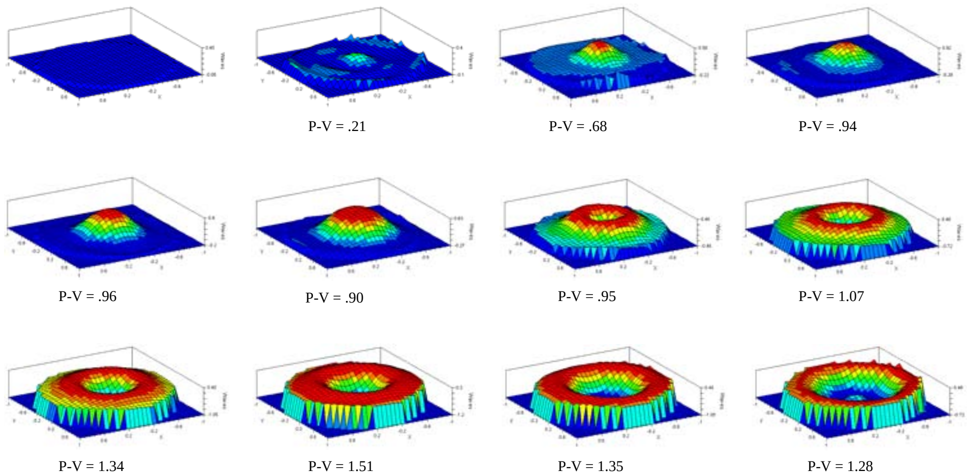

Figure 3. Evolution of surface profile on the membrane shown in Figure 2.

Conclusion

This novel approach to increase the bandwidth of an adaptive optic is complex. Membrane mechanics may be reasonably well understood, but nozzle and gas dynamics are not. This entry level experiment suggests that 50 to 100 kHz operation may be obtainable but more must be done to quantify the performance opportunities. The spatial extent of actuation is a significant unknown, but experimental results suggest that control can be applied below a one centimeter diameter region. A decreased gap depth and a smaller nozzle diameter would help reduce the actuation area and substantially increase the frequency of the first resonance. Note that polymer based adaptive optic could be built to diameters approaching a meter giving rise to the idea of an adaptive primary mirror. The combination of these two new technologies creates interesting possibilities but that contemplation is left to the reader.

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