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14. ABSTRACT The research performed under this grant developed the structural mechanics of an adaptive optic system consisting of a membrane reflective surface stretched over a pressurized cavity. The work presented here starts under the assumption that the quality of optical system is described by Zernike Polynomials and proceeded by coupling the Zernike Polynomials to the membrane dynamics and provide several methods to control the membrane surface and hence the optical quality. Two actuation approaches are presented: 1) using piezoelectric elements near the boundary of the membrane and one using control of the acoustic pressure in the cavity behind the membrane. Analytical models, experimental and numerical validation and closed loop control are accomplished.					
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Introduction: This research was motivated by AFRL's efforts in Directed Energy to examine the use of membrane optics with control systems to replace heavy metal and glass surfaces. Two approaches were taken: the use of piezoelectric elements to control the shape and vibration of the membrane surface and the use of pressure gradients to control the membrane surface. While motivated by practical problems, the research centered around modeling, experimental verification, and numerical validation of a multi-physics system consisting of actuation mechanisms, acoustic cavity, optical properties and membrane mechanics. This research resulted in two PhD dissertations (Jamil Renno and Pablo Tarazaga), six journal articles (more to come) and ten conference papers. Detailed descriptions of the research are available in the literature (references given below) and readily available to the public. Thus this report presents only a summary of the results discovered during the course of this research.

Adaptive optics requires a method of actuation to change the surface properties of a reflective membrane surface. Previous research has focused on boundary and tension control devices as the means to perform this actuation. The distinguishing feature of this research was to also employ a piezoceramic based actuation system and to effect the pressure distribution across the membrane and hence extend adaptive membrane optics by providing distributed control of the reflective surface. Initial theoretical considerations indicate that this would allow controlling optical aberrations not currently addressed by boundary control, greatly improving the optical quality. Because this approach requires a thin film of fluid between a backplane and the optical surface, the research objectives involved modeling in four disciplines (fluids, structures, optics and structural control) and understanding the interactions between them.

Summary of Results

Piezoelectric Control The main idea here is to use piezoelectric elements layered into the membrane surface near its edges. Complete details of this approach can be downloaded from <http://scholar.lib.vt.edu/theses/available/etd-09052008-043809/> through the Virginia Tech library system or from the papers listed below.

The control of a strip membrane using a piezoceramic-based composite has been modeled using energy methods and successfully compared with experimental data in a vacuum chamber. This validated model (less than 2% error) has then been used in a control scheme to reduce vibrations in membrane-based mirrors and to provide an element of shape control useful for adaptive optics.

The sliding mode technique was used to control the deformation of a membrane mirror strip augmented with two macro fiber composite bimorphs located near the ends of the strip. The first bimorph is actuated in bending whereas the second is actuated axially. The structure is modeled as an Euler-Bernoulli beam under tensile load and the macro fiber composite patches are modeled as monolithic piezoceramic wafers. In order to cast the system into a finite dimensional state space form, the finite element method was used and the model presented accounts

for the dynamics of the augmented bimorphs. The membrane strip is placed under uniform tension. Since one of the bimorphs acts axially, the resulting tension in the membrane strip is discontinuous at the location of this bimorph and consequently, the obtained model is nonlinear. First, the model was validated experimentally by considering the system in its quasi-linear state, then the control problem was solved.

A regulation problem by using the sliding mode technique was developed as the solution approach. Additionally, to allow coupling this system with an adaptive optics scheme, the shape control problem was also considered. The control law utilizes both actuators: the bending and axial bimorphs. However, a system singularity dictates using a switching command to avoid this singularity. Various examples are presented for the regulation and shape control problems. The simulation results demonstrated the efficacy of the derived control law. Other results include the reduced order modeling of a circular membrane with macro fiber composite actuators integrated into the membrane. This extends the previously derived results for a "strip" to a full membrane and provides a low order model for use in design and control analysis. The following results summarize the research performed for the piezoelectric control system:

1. Modeling of a membrane strip and corresponding experimental validation
2. Integration of piezoelectric elements into the membrane strip and design and validation of the corresponding shape and vibration controllers
3. Modeling of a circular membrane with integrated piezoelectric actuators
4. Controller design, based on the above models, for correction of optical aberrations.

Pressure Control This work has demonstrated that the novel application of internal acoustical excitation possesses the potential use for vibration suppression of optical membranes in pressurized coupled cavity-membrane structures. Dynamic control is essential for the adequate performance of thin-film membrane mirrors. Using this new approach for vibration suppression can alleviate some of these disturbances induced on the system and attack optical modes not reachable using the piezoelectric approach mentioned above. This results in a faster attenuation of the system and thus, permitting the employment of the satellites by reducing inconvenient interruptions due to vibrations.

The ability to use acoustic excitation for vibration suppression was demonstrated by initially constructing a set of models that accurately described various phenomena. The radiation produced by a membrane due to its out-of-plane vibrations was addressed, as the energy loss in the coupled cavity system is the result of sound radiation to the far field. This contributes greatly to accurately model the natural frequencies and the damping of the system. Modeling of a membrane with considerations to the sound radiation effect in air has the advantage that it eliminates the need to test the setup in vacuum conditions, which can be an expensive and tedious experiment to conduct.

These results additionally proved that the concept of proportional damping, or modal damping for a membrane immersed in air, is not an appropriate way to account for damping in the system. In the cases discussed here, the mass loading effect of the air surrounding the membrane caused a 47% shift in the first symmetric mode of the membrane, and 25% in the second symmetric mode.

To validate these findings, a representative experimental setup of a membrane in air was constructed. An innovative strategy was developed to obtain a membrane with uniform tension. This was essential in being able to validate the model. Once a representative model of the membrane was obtained, the membrane was coupled to a cavity to obtain a coupled membrane-cavity system. This was accomplished by using an impedance-based modeling approach, where the subsystems are modeled independently and then coupled at the interface. This resulted in two separate models described here as the actuation model and the disturbance model. The actuation model describes the behavior of the membrane, radiation and cavity due to an acoustic excitation located at the base of the cavity. The disturbance model describes the behavior of the coupled system due to an incident force on the membrane. The coupled behavior of the system drastically changes the dynamic behavior of the membrane. The first mode of a membrane in vacuum couples very strongly with the zero mode of the cavity, driving its dynamic behavior to very low frequencies in the coupled response. The first mode of the coupled membrane exhibits the behavior of a clamped circular plate, which is mainly due to pressure in the cavity having its maximum value at the walls. The second mode of the coupled membrane is similar to the second mode of the membrane in vacuum, and does not exhibit as much coupling as the first mode as it is more resilient to shifts in frequency due to changes in the cavity, or air. In the same manner, the opposite is true for the first mode.

Changes in tension, membrane density, and membrane thickness, have a drastic effect on the second coupled mode of the membrane, but not as much in the first coupled mode of the membrane. A representative test setup was additionally built to validate the coupled membrane cavity models. The models provided close agreement in the overall response, operation deflection shapes, damping, and natural frequencies of the experiments. The natural frequencies were estimated within and overall average of less than 2% error for all models.

The end goal was achieved by putting together all of these models for the purpose of suppressing the vibration of the membrane, which was carried out theoretically and experimentally. A *Positive position feedback* approach was used in the vibration suppression of the membrane with extensions to *positive velocity* and *positive acceleration feedback*. *Positive position feedback* was implemented experimentally which resulted in a 16 dB attenuation of the first mode. These results will soon be available on line as part of the PhD dissertation of Pablo A Tarazaga by searching the Virginia Tech library system.

Summary: A membrane mirror works by optical rays reflecting off of its surface and corrections to the optical image being made by active control resulting in an

adaptive optical system. The research performed under this grant developed the structural mechanics of an adaptive optic system consisting of a membrane reflective surface stretched over a pressurized cavity. The work presented here starts under the assumption that the quality of optical system is described by Zernike Polynomials and proceeded by coupling the Zernike Polynomials to the membrane dynamics and provide several methods to control the membrane surface and hence the optical quality.

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