Active Composite Membrane Mirrors

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Abstract

Fabrication of composite sandwich panel mirrors has advanced sufficiently in surface accuracy and thermal stability to consider a thin composite membrane supported by rigid active supports for a large space mirror. We are carrying out a technology development with a 0.5-meter diameter, 0.5-mm thick composite membrane on a 36-actuator support. Measurements will be made of the controlled figure at ambient and low temperatures to determine the figure accuracy and stability and the validity of the mathematical performance analysis.

Introduction

This work brings together three developing technologies to produce large space optics. It combines composite mirror technology using a thin composite membrane, active rigid support being developed by the University of Arizona for the NGST (Burge *et.al*, (1998), and thin deposited glass coatings for composite optics (Woida and Hoffmann, 1997 and Woida *et.al*.(1998). The Active Composite Membrane Mirror Concept is similar to the NGST vision proposed by Burge, with the exception of replacing the thin glass shell with a composite membrane to make the reflective surface. This has the potential advantages of a much less fragile mirror, simpler fabrication, and lower weight. This approach departs from traditional composite mirror panel construction by replacing the static core material normally used to maintain the shape of the relatively flexible face-sheet, with an actuator based support system. The deposited glass technology allows for optical surface figuring to improve surface smoothness and correct surface variations in the composite membrane without damage to its structure . When these elements are combined, we have a method of producing an ultra-lightweight mirror for the generation of telescopes to follow the NGST.

The required technologies are already under independent development and we are undertaking the first steps at bringing them together during the spring of 1999.

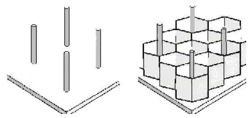

Figure 1 Membrane with actuator supports

The Active Composite Mirror Concept

The concept for the active composite mirror is a composite membrane, or shell, supported by a set of rigid mechanical actuators, which are in turn supported by a truss or frame structure. The membrane is a carbon fiber reinforced plastic (CFRP) shell. The actuators are used to provide a rigid support and initial correction and occasional updating of the surface figure. The mirror requirements are given in Table 1. A severe constraint is the areal density, with a goal of 5 kg/m^2 for the entire mirror with an assignment of 1/4 of this, about 1.25 kg/m^2, for the membrane.

This allocation of weight for the membrane can be entirely devoted to the shell, resulting in a thickness of a little less than 1 mm, or could be shared between a shell and a very light-weight open-core backup structure which provides stiffness against distortions on a scale smaller than the actuator spacing. CFRP core material is commercially available with approximately 0.5 cm cell size and which, for a 1 cm depth, has an areal density of 0.46 kg/m^2. Figure 1 shows a sketch of a bare membrane and a membrane with open core backup, both supported by rigid actuators bearing directly on the membrane.

We have chosen as a surface figure requirement, diffraction limited imaging at a wavelength of 2 µm, which implies a surface departure from the desired shape of less than 0.08 µm rms. This cannot be achieved directly with a replicated CFRP surface, but can be achieved by polishing and figuring a thin glass surface deposited on the surface.

Size	4-meter segment		
Figure accuracy	2 µm wavelength diffraction limited		
		0.08 µm rms	
Environment	Space		
		Temperature	< 77 K
Areal density	Overall (membrane, actuators, structure)		
		< 5 kg/m^2	
		Membrane	< 1.25 kg/m^2
CFRP density		~ 1.6 gm/cm^3	
Required membrane thickness		< 0.08 cm	

State-of-the-art Composite Mirror Performance

Composite mirrors, primarily used for radio and sub-millimeter reflectors, are typically formed as a sandwich panel from two CFRP face sheets of thickness 1-3 mm glued to a core material several cm thick. The face sheets are replicated against a precision mold. The core material has thin walls and a hexagonal or similar structure. It can be made of aluminum or of the same composite material as the face sheets. In recent years the technology of fabricating these mirrors has improved to provide thermal stability and surface figure suitable for sub-millimeter and far-infrared reflectors and approaching the requirements of mid- and near-infrared. Our knowledge of the performance of CFRP mirrors comes primarily from these sandwich panels. However, since their performance depends very much on the quality and performance of the face sheets, there is some justification in expecting some of the measurements to apply to a bare, or open core backed, actuator supported membrane of thickness similar to that of the face sheets of sandwich panel mirrors.

Table 2 gives an example of the thermal stability and figure accuracy achieved by a CFRP sandwich panel mirror of 0.5-meter diameter with a spherical surface of 3-meter radius of curvature, which we refer to as Marshall-4.

The replicated figure and the change in the figure over the temperature range -60 to 20 C were measured with the 10.6 µm wavelength phase-shifting interferometer shown in Figure 2. We have been operating this instrument in a long term program of testing both the surface figure accuracy and thermal figure stability of composite optics using a low temperature chamber. In the figure the spherical curved wave front formed from a small lens is reflected from the mirror surface and compared with a flat reference mirror in the interferometer.

Thermal stability -	effective coefficient of thermal expansion (CTE) from focus change 0.66×10^{-6}/C
Replicated figure accuracy	~ 3 µm rms

More details of the change in the surface of Marshall-4 with temperature are given in Figure 3 which shows several Zernike polynomial coefficients for the change in the figure from its room temperature shape. The numbers in the figure are the peak-to-valley size of the figure change for the particular Zernike term. The largest change is in the focus, which is used to determine an effective coefficient of thermal expansion (CTE) for the mirror. The other terms show changes less than 0.1 µm. The change in the residual rms after subtracting the Zernike terms is less than measurement error, indicating very little small scale change or rippling.

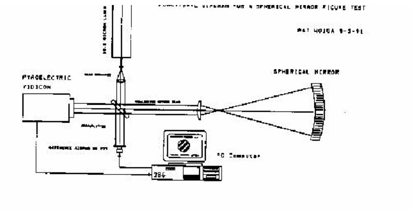

Figure 2 Phase modulated 10.

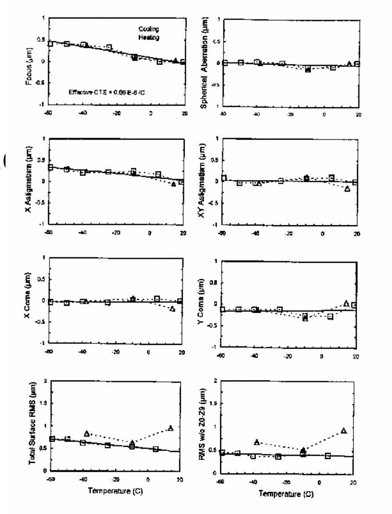

Figure 3 Zernike polynomial coefficients for 0.5-m diameter composite sandwich panel mirror, Marshall-4. The values are the difference between the surface figure at the specified temperature and that at 18 C. The anomalous points are an artifact from noisy pixels

Figure Improvement with a Deposited Glass Coating

As part of our research with composite mirrors we have investigated several techniques for adding a thin glass layer to the surface of a composite panel to allow for improvement of the surface over the original manufactured accuracy. CFRP panels are fabricated by replication of the front surface against a precision mold. The key element for the panel replication and ultimate panel stability is the ratio of fiber to matrix material in the composite. High replication accuracy requires a resin-rich composite surface while high thermal stability a resin-poor, or fiber rich, composite. So to achieve a surface figure warranted by the thermal stability, some process to improve on replication accuracy is required. With such a process, it has been possible to achieve surface figures suitable for infrared applications and, at the same time, reduce the costly requirement for near-optical precision of the replication mold.

We found that depositing a thin glass layer (10-200µm) is superior to directly figuring a composite face sheet. Direct figuring of the replicated surface can quickly break through the resin poor surface of a stable panel to expose the fibers. Breaking the fibers compromises the structural design of the composite. It also leaves a non uniform surface texture from polished epoxy to fibers that will not polish, broken fibers can contaminate and ruin the polishing effort, and cause irregular patches of surface scattering. We have previously reported evaporative coating of CFRP panels with glass (Woida and Hoffmann, 1997) and are currently working with chemically deposited glass (Woida and Hoffmann, 1998). These coatings are durable and can be ground, polished, and figured by conventional optical techniques.

Vacuum deposited SiO	Thickness	< 40 µm	
Chemically deposited glass (SiO_2)	Thickness	>10 µm	< 2 mm

Figure Quality Can be improved to infrared quality by polishing and figuring

The deposited glass technique is superior to adhesively attaching a glass plate to the panel surface. A glass plate tends to be of millimeters rather than microns thick, and significantly adds weight to the resulting mirror. Thinning a glass shell is a difficult task compared to building up a deposited coating. The deposition method also insures a complete fill of the “valleys” in the surface, providing a void-free interface with the composite material with no adhesive bond layer and with a good CTE match.

A summary of glass coating is given in Table 3. Figure 4 gives a macro-photograph of part of a CFRP sandwich panel mirror with a deposited glass surface. The deposited glass and the CFRP face sheet were both 2 mm thick in this example. This photograph shows a portion of the glass surface and a cross section of the glass, face sheet, adhesive bond layer, and aluminum core.

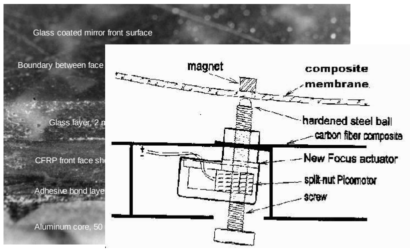

Figure 5 Composite membrane with motor driven screw support

Figure 4 Macro-photograph of a CFRP mirror with a deposited glass surface. The magnified image was obtained at an oblique angle to show both the surface and edge of the mirror.

Actuator Supported Membrane Experiment

As part of our work for the NASA Institute for Advanced Concepts (NIAC), we are carrying out a technology development program to demonstrate a small model of an actuator supported composite mirror. The characteristics of the model are given in Table 4. Optimum design analysis and fabrication of the membrane is being carried out at Composite Optics Inc. The membrane will be supported on a 36-actuator support with actuators used in a previous NGST experiment. A cross section drawing of the membrane and one actuator is shown in Figure 5.

Measurements will be made using the interferometer shown in Figure 2. These will include measurements of the membrane figure as replicated and the corrected figure supported by the actuators at room temperature and at a variety of temperatures down to -60 C. The planned measurements are given in Table 5. These measurements will be used to determine the figure accuracy and stability and the validity of the mathematical performance analysis.

ameter	0.5-meter
Actuators	36 with motor-driven screws
Membrane	0.5 mm thick bare composite membrane

Surface figure of membrane as replicated

Figure with actuators optimally adjusted

Correction forces

Small scale uncorrected errors

Local distortion induced by actuators

Figure change when cooled to -60 C

Possibly figure change when cooled to ~ 77 K

Summary and Conclusions

1. A composite membrane is a viable alternative to glass for an ultra lightweight actuator-supported space mirror.

2. Composite sandwich-panel mirrors have achieved thermal stability approaching the requirements for an infrared telescope in space.

3. A deposited glass surface, polished and figured, can provide a figure suitable for an infrared mirror.

4. An experiment is underway at the University of Arizona and Composite Optics Incorporated to provide a 0.5-meter diameter demonstration of an actuator supported composite membrane mirror.

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