Structural Analysis of the 0.4 meter Lightweight CFRP OTA at the NRL

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ABSTRACT

A 0.4 meter Carbon-Fiber Reinforced Polymer (CFRP) Optical Telescope Assembly (OTA) has been developed as a prototype by the Naval Research Laboratory (NRL) and Composite Mirror Applications (CMA). All components of this OTA have been made from the CFRP material, including the optics, and has dramatically reduced the weight of the overall structure. The use of this material increases the portability of this OTA and can reduce the cost of future telescopes. However, because this material is more lightweight than the materials traditionally used in OTA construction, the vibration characteristics are different and obtaining optical surface quality is non-trivial. This paper investigates certain structural properties of this OTA through the use of accelerometers attached and measurements taken statically and dynamically. Some measurements include the movement of the telescope at different speeds indoors and outdoors, as well as on and off a traditional tripod. Also, an impulse response measurement is obtained by tapping a weight to the OTA structure and the damping time is measured through the oscillations measured by the accelerometers. This OTA prototype is being developed for two future projects. The first being the development a 1.4 meter CFRP OTA for the upgrade of the Naval Prototype Optical Interferometer and the second being a lightweight deployable 0.4 meter CFRP OTA with adaptive optics. Furthermore, the properties of this CFRP material not only reduce the weight of the OTA, but the coefficient of thermal expansion is controlled such that this approach is very attractive for space-based telescopes which, because of the light weight, can be deployed into space at a dramatically lower cost than traditional telescopes.

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1. INTRODUCTION

The Naval Prototype Optical Interferometer (NPOI) is the world's only long baseline optical interferometer operating in the visible region, i.e. wavelengths below 0.8 μm. It is also the only optical interferometer capable to recombine up to six beams, from different apertures, simultaneously. A diagram of the current status of the NPOI is shown in figure 1, where the squares represent existing pads where telescopes can be mounted or moved to, and the circles represent current usable apertures. Currently the NPOI uses *Siderostats,* i.e. flat mirror that track the object in the sky and redirect its light into the beam relay system. These apertures are 0.5 m in diameter but to avoid atmospheric turbulence problems they are stopped down. Thus the overall sensitivity of the instrument is limited to objects with a visual magnitude of 6. Recent investigation has aimed at increasing the sensitivity of the interferometer by implementing larger apertures for light collection. However, building dozens of meter class telescopes for array population is too costly, and building several telescopes that can be moved from station to station is impractical considering the weight of traditional telescopes. Therefore, the use of Carbon Fiber Reinforced Polymer (CFRP) materials was explored for telescope construction. There are several advantages to using CFRP for telescope construction, including an order of magnitude decrease in weight, allowing easier transportation from station to station on the array. As all components of the telescope, including optics, are constructed from composite materials having a low coefficient of thermal expansion, dimensional changes due to temperature variations can be minimized. Also, since all optics are made from a single high precision tool, duplicate components can be manufactured for much less than traditional steel and glass telescopes.

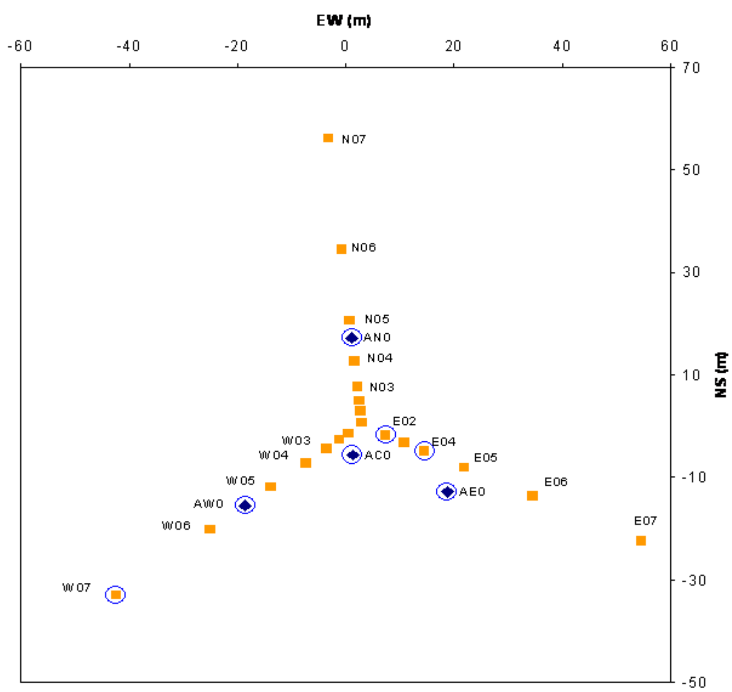

Figure 1: Lay-out of the inner portion of the NPOI interferometer. Squares represent existing pads, the circles are existing apertures mounted on pads.

The NPOI will be integrating 1.4 meter CFRP telescopes with its array upon delivery in 2006. However, testing of the material properties of CFRP, the optical quality of the mirror surfaces, and integration of the Optical Telescope Assembly (OTA) have been ongoing for over a year. Small aperture (0.4 meter) telescopes were manufactured for testing the mechanical properties of the OTA and the optical quality of mirrors. Samples of the material for the 1.4 meter telescope were sent to Northern Arizona University (NAU) for testing.

2. SYSTEM OVERVIEW

The 0.4 meter telescope is a scale model of the 1.4 meter telescope and was constructed to allow preliminary testing on the OTA. The 0.4 meter telescope, shown in Figure 2, has a 16 inch primary mirror and an f/# 3.1. The OTA was mounted on a commercial 8 inch telescope mount using adapter plates to extend the telescope arms as shown in figure 2. This configuration allowed ease of alignment for the optical testing and provided a movement mechanism for the mechanical testing. The optical testing consisted of Ronchigram recording and analysis. The optical testing is described in Section 3. This 8 inch mount also provided a movement mechanism for the mechanical testing. The impulse force response of the telescope was measured at various declinations to determine the relaxation time constant of the OTA.

In addition to the optical and mechanical testing performed on the OTA and temporary mount, materials testing was performed on the low and high modulus materials used in both the construction of the 0.4 meter prototype and the 1.4 meter deliverable telescope. The results of this analysis are discussed in Section 5.

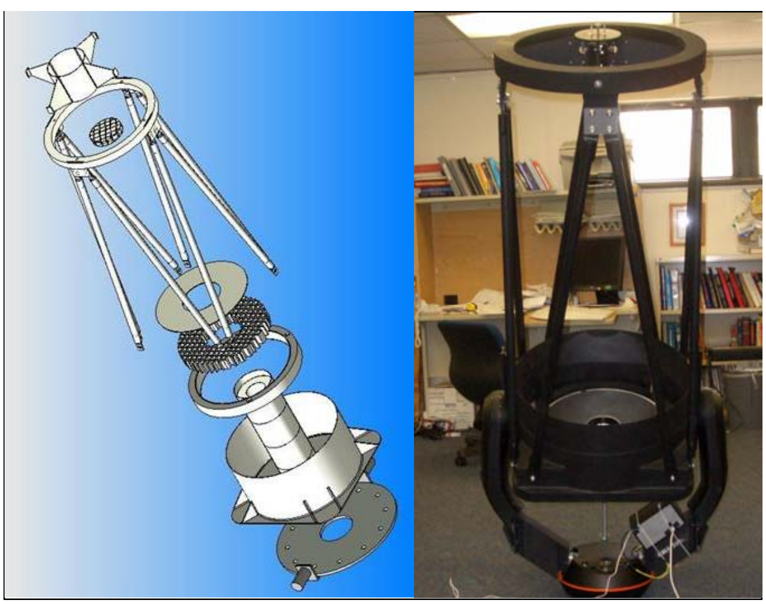

Figure 2: 0.4 meter telescope

3. OPTICAL ANALYSIS

The Ronchi test, introduced by Vasco Ronchi in the twenties [1], is a very simple and powerful method to evaluate and measure aberrations in an optical system. The basic principle resides in the fact that when a ruling is placed near the center of curvature of a mirror, the image of the grating is then superimposed on the grating itself producing a moiré pattern is usually called *combination* fringes. While the interpretation of the combination fringes is quite difficult, software analysis can be performed by either simulating the Ronchigram in a ray-tracing package like Zemax, or performing analysis similar to traditional interferometric fringes. For sake of this paper we present an example of measured data compared with two simulated Ronchigram with the same spatial characteristics of the grating used for the lab testing data.

In figure 3 the lab test Ronchigram is compared with a Ronchigram obtained using a simulated diffraction limited 16” mirror with the right parameters to match the measured one, and another mirror with a mismatch in radius of curvature resulting in more than one wave of defocus present in the system. It is clear that, beside some turning of the combination fringes at the edge of the mirror, the measured Ronchigram matches very well the diffraction limited analytic Ronchigram.

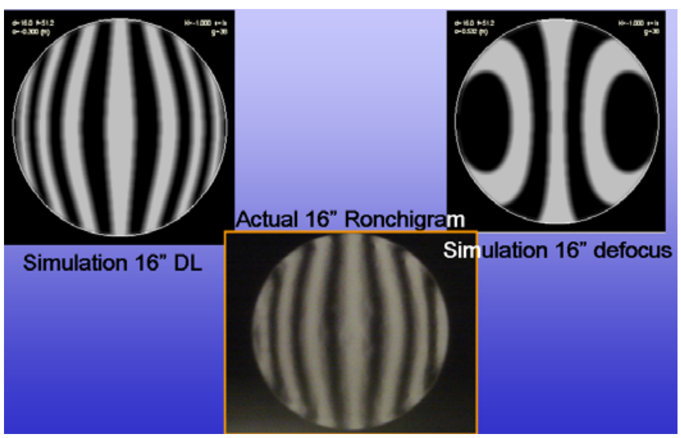

Figure 3: Measured Ronchigram (bottom) and simulated Ronchigrams.

4. MECHANICAL ANALYSIS

The OTA and mount configuration was kept stationary, and the impulse response of the structure was measured by tapping a weight to the telescope and using accelerometers to measure the movement of the structure. The impulse response, seen in Figure 4, by inspection was of the form of,

$$Ae^{-\alpha t}\left[B\sin(\beta t)+C\cos(\gamma t)\right]+b \tag{1}$$

where α is the damping coefficient, and β and γ are frequencies of oscillation.

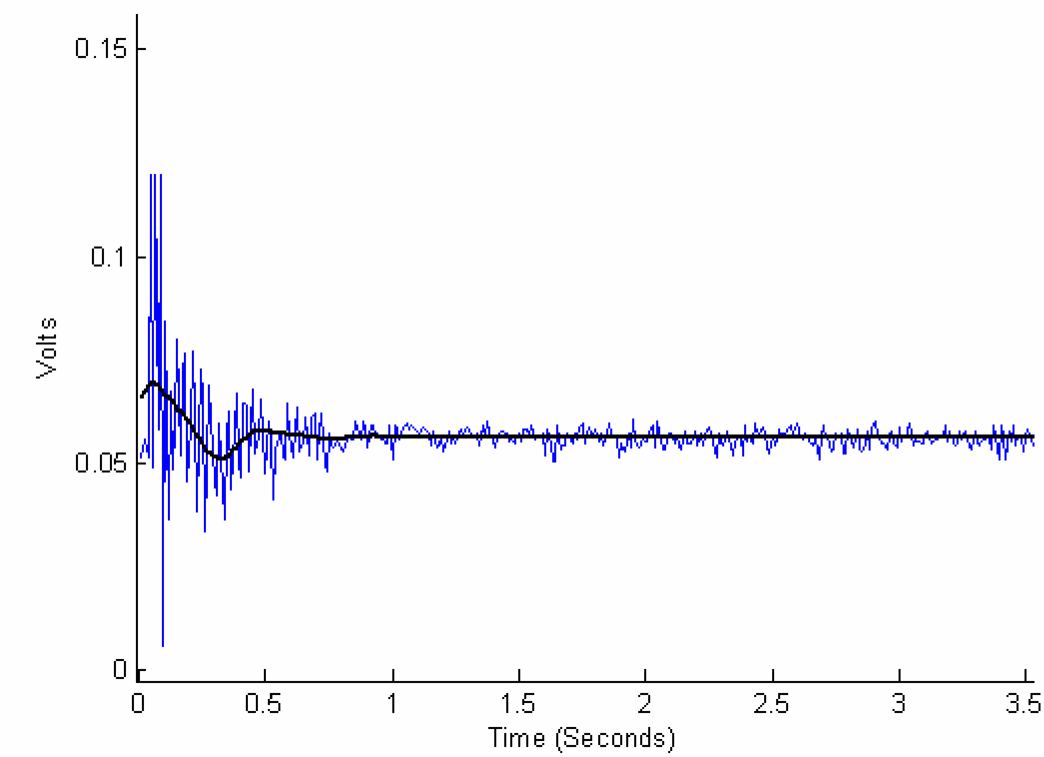

Figure 4: Plot impulse response to a weight hitting the structure of the 0.4 m telescope with curve-fitted function overplotted.

Table 1: Average coefficients calculated from Matlab

α	β	γ	b
5.3061 s^{-1}	14.6149 s^{-1}	27.9204 s^{-1}	0.056508 s^{-1}

Matlab was used to curve-fit the data to this function and thereby calculate the damping coefficient. Values of the coefficients can be seen in Table 1. Multiple data sets were taken for different declinations and were averaged together. The calculated damping coefficient was found to be 5.3061 s^{-1}. This implied a time of 0.1885 s for the oscillation to reach the 1/e value. A plot of the damped envelope function can be seen in Figure 5. With a relaxation time of about 0.2 s, the telescope will not be affected by wind buffeting which occurs at roughly 1 Hz.

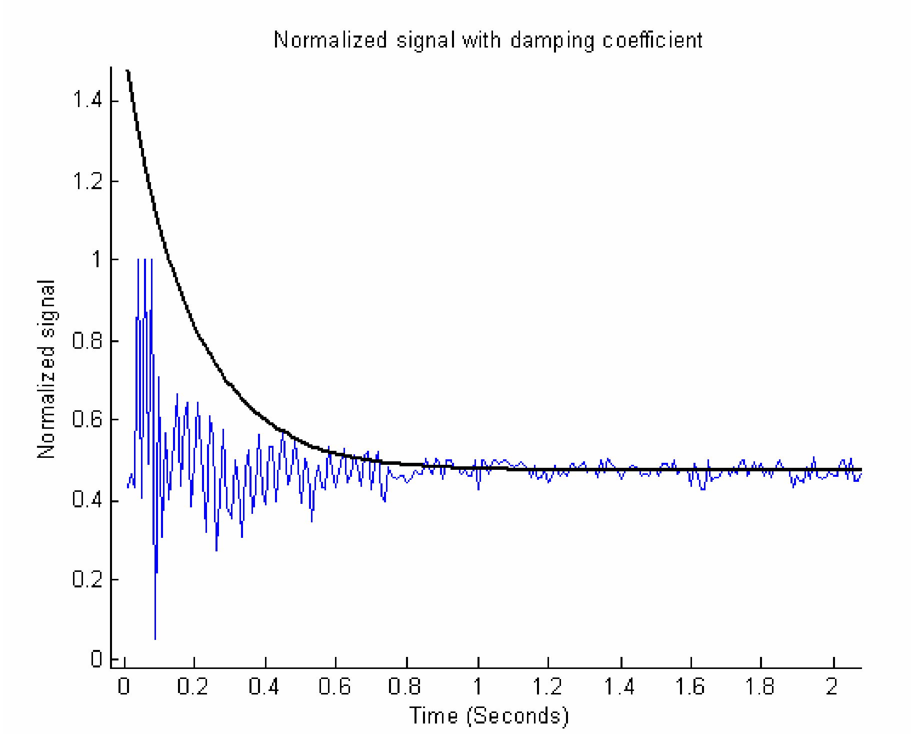

Figure 5: Plot impulse response to a weight hitting the structure of the 0.4 m telescope with damped envelope function overplotted.

5. MATERIAL PROPERTIES

Coefficient of thermal expansion

Coefficient of thermal expansion (CTE) tests were performed for two discrete temperature ranges: 1) a hot cycle (70°F to 270°F) and 2) a cold cycle (70°F to -27°F). Each coupon was affixed with a high temperature 0°/90° strain gage rosette and temperature sensor. The composite coupon was wired in a half bridge configuration with a 2024-T4 aluminum plate with known CTE of α_r=23.2+E-6/°C. The strain in the composite at a given temperature is:

$$\varepsilon_c = \alpha_r \Delta T + \varepsilon_a \quad (2)$$

where ΔT is the difference in testing temperature to starting temperature and ε_a is the reading from the strain gage half bridge configuration. Figure 6 shows a CTE sample with high temperature strain gages and temperature sensor. The strain vs. temperature plot (Figure 7) allows determination of both longitudinal and transverse CTE by calculating the slope of the line. Slopes were taken over the entire length of the line yielding an averaging effect throughout the temperature range of interest.

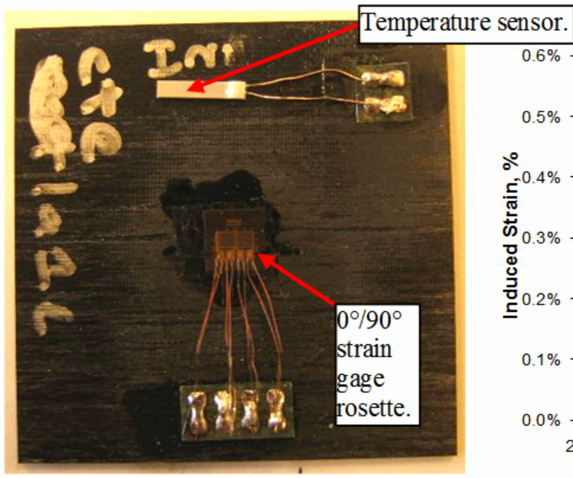

Figure 6: Lamina CTE sample.

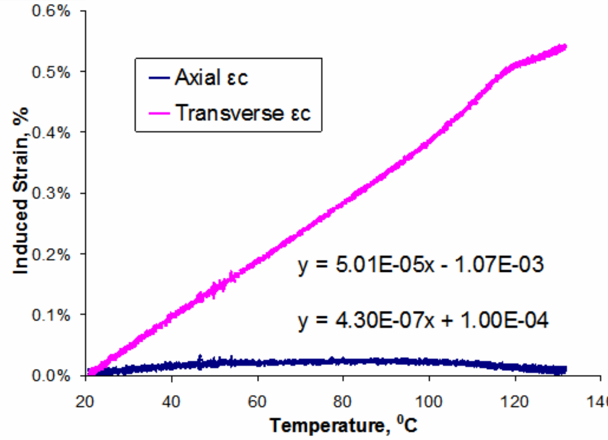

Figure 7: Strain-temperature plot for axial and transverse directions.

Fiber volume fraction

The percent of fibers within the composite material is determined using the chemical digestion method [3]. In this method, a square sample of eight plies was weighed and then exposed to nitric acid which dissolved only the matrix material. After drying the remaining fibers in a laboratory oven, they were weighed such that the percent of matrix and fibers can be determined. Since the fibers support most of the tensile load and the matrix supports most of the compressive and shear loads, an ideal balance is a FVF between 60% to 65% [4].

6. SUMMARY

A prototype 0.4 meter telescope has been manufactured out of Carbon Fiber Reinforced Polymers to allow testing for a future 1.4 meter telescope to be implemented for a reconfigurable baseline at the Naval Prototype Optical Interferometer. This lighter material allows ease in portability, but the optical, mechanical and material properties were examined in this paper to determine how effective this novel approach was. The optical testing showed a nearly identical figure to the ideal based on the Ronchigram tests. The imperfections at the edge necessitate stopping the aperture down slightly to avoid optical aberrations. The mechanical testing showed the damping time constant of the optical telescope assembly was much less than the frequency of wind buffeting, making the setup ideal for observatory setup. Characterization of the two material systems used showed clear advantages of the use of composite materials in lightweight, dimensionally stable telescopes.

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BIOGRAPHY

Christopher Wilcox is a graduate student in Electrical Engineering at the University of New Mexico as a PhD candidate. Currently working at the Naval Research Laboratory working in the field of Adaptive Optics and Wavefront Sensing & Control, his research areas include optics, adaptive optics, mathematics and hardware implementation. He has earned a Bachelor of Science in Electrical Engineering at the New Mexico Institute of Mining and Technology and has just completed his Master of Science in Electrical Engineering. Previous work includes working at the National Radio Astronomy Observatory at the Very Large Array outside of Socorro, New Mexico.