Engineering Notes

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Thermal Deformation Characteristics of a Six-Inch Graphite/Epoxy and Ultra-Low-Expansion Mirror Telescope

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Introduction

GRAPHITE/EPOXY (gr/ep) housings for telescopes are being considered as possible replacements for metallic housings that cannot maintain requirements of <1 arcsec boresight stability for ± 15°C thermal soaks and 1°C diametral thermal gradients. A graphite/epoxy and ultra-low-expansion mirror telescope has been designed, assembled, and tested to verify predictions of thermal insensitivity of the assembly. Test data taken in a thermal vacuum chamber show assembly soak axial coefficient of thermal expansion (cte) of $<0.05/10^6$ in./in./°C and diametral thermal expansion (cte) of <0.09 arcsec/°C. The axial coefficient of thermal expansion for the assembly is <1/440 of that of aluminum. Thus the thermal insensitivity of the gr/ep material has significant advantages over metals. The test methods described in the paper to obtain expansion coefficients are relatively unique. Analytic predictions that evaluate optical performance including thermal deformations also are presented.

Graphite/Epoxy vs Metals for Telescope Housing Materials

The thermal deformations for the housings are proportional to material thermal conductivity K_i, coefficient of thermal expansion α_i, and elastic moduli E_i (for particular geometrics). An axial thermal deformation (despace) figure of merit to be minimized is

$$D_i \equiv \alpha_i / K_i E_i$$

The values of D_i for gr/ep vs typical metals (aluminum, titanium, beryllium) are $\approx 10^{-15}/15$ vs 1.7×10^{-15} to 15×10^{-15}, so that gr/ep minimizes D_i by at least 25 vs metals. In addition, thermal-gradient-induced tilts (causing boresight shifts) for thin housings (tubes, box structures) vary approximately as thickness t for gr/ep (because of high transverse gr/ep α_i) and as depth d for metals. The figure of merit to be minimized is (α/Ed). Thus, since

$$(\alpha/E)_{\text{gr/ep}} / (\alpha/E)_{\text{metals}} \times (t/d_{t/d=1/80}) < 1/15$$

gr/ep has advantages vs metals for minimizing thermal-gradient-induced boresight shifts from tilts. The theoretical predictions and (primary) experimental results of this paper are to validate thermal deformation minimization for a 6-in gr/ep telescope housing (and ultra-low-expansion mirrors).

Telescope Requirements and Design

A gr/ep telescope housing with flanges and three-leg gr/ep secondary spider, along with ULE (ultra-low-expansion) primary and secondary mirrors (see Fig. 1), was designed. The gr/ep housing and secondary spider both were constructed by cocuring 0.007-in. gr/ep plies of GY-70/X-30 "pseudoisotropic" material at 275° with the 16 plies placed at $(0°, 45°, 90°, 135°)_{2s}$ angles to each other in each module. The parts were cocured in a graphite cylindrical tool. The resulting balanced ply construction should provide nearly equal in-plane material properties with $E_l = 1.5\times10^7$ psi,- $K_l = 20$ Btu-ft/ft^2 – hr°F, $\alpha_l = 0.05/10^6$ in./in./°C. The balanced laminate has plies that each have a $\alpha < 0.01/10^6$ in./in.°C in the fiber direction, but α up to $0.4/10^6$ in./in./°C at other angles. However, the laminate is tailored for this application to give $\alpha < 0.05/10^6$ in./in./°C in all directions. The out-of-plane coefficient of expansion of $24/10^6$ in./in./°C, 0.112-in. housing tube thickness, and out-of-plane E_2 has a predicted tilt sensitivity of 0.90 arcsec for a 1.0°C diametral thermal gradient (4.81 arcsec for an aluminum tube of the same dimensions).

Composite Telescope Thermal Deformation Results

The testing of the gr/ep telescope is outlined as follows: 1) room-temperature Fizeau interferometric patterns during three different days; 2) room-temperature Fizeau interferometric patterns at HRC, 3) thermal vacuum testing during 7°-35°C soak temperature (control to +1.0°C soak temperatures (control to ±0.1°C). These tests gave us room-temperature baseline data and soak data (and gradient data). The soak and gradient testing let us determine axial thermal coefficient of expansion and tilt sensitivity to soaks (and gradients).

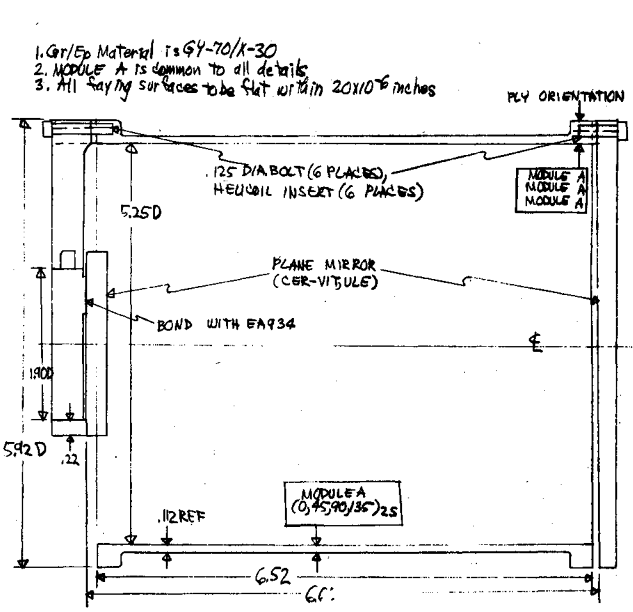

Fig. 1 Telescope drawing (gr/ep, mirrors) assembly.

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Index categories: Materials, Properties of; Structural Composite Materials.

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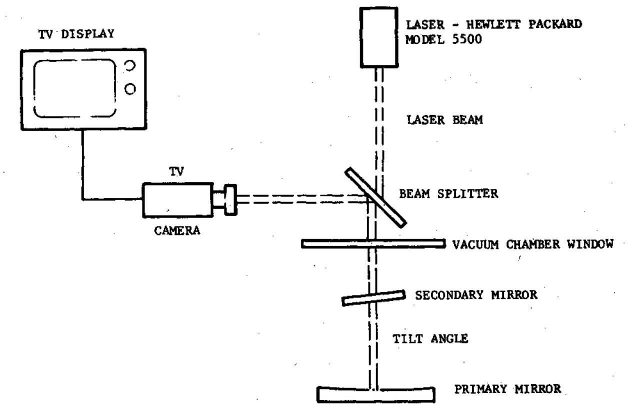

Fig. 2 Optical schematic.

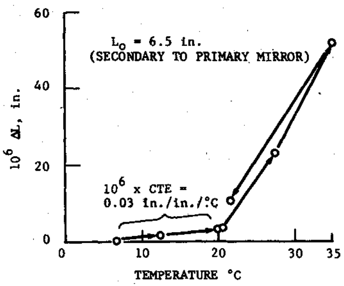

Fig. 3 ***GD/C*** **ΔL (despace) vs temperature.**

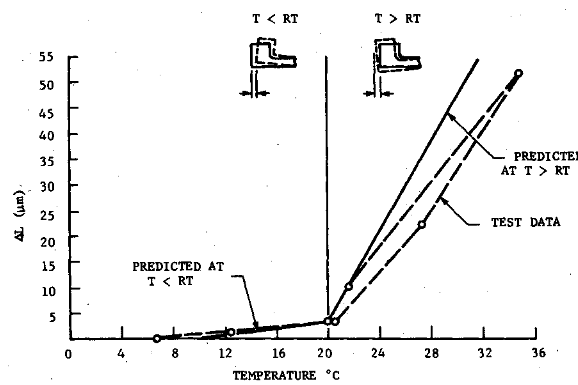

Fig. 4 Plot of predicted vs test despace of graphite/epoxy telescope.

The thermal deformation measurement setup is shown schematically in Fig. 2. The six thermocouples on the secondary spider (three) and on the support plate (three) provide temperatures to determine average soak temperatures and axial and diametral thermal gradients for each fringe pattern observation (and photographs). Axial despace changes are found from movement of fringes past a fixed point, whereas mirror relative tilts are found from fringe spacing changes. Electro-optic equipment counts fringe movement and automatically plots the fringe movement vs one support flange thermocouple temperature. The axial despace changes vs temperature obtained during initial testing are shown in Fig. 3. The data show a CTE of $0.03/10^6$ in./in./°C from 6° to 20°C but $0.5/10^6$ in./in./°C from 21° to 33°C. The near-zero CTE of $0.03/10^6$ in./in./°C was expected, but the higher value of $0.5/10^6$ in./in./°C was higher than expected (design value of $0.05/10^6$ in./in./°C). We conducted a finite-element analysis that predicts a CTE of $0.49/10^6$ in./in./°C (see Fig. 4). The analysis shows that the mirror despace is greater above room temperature (20°C) than below room temperature because of mirror registration

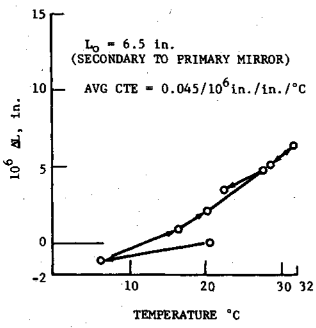

Fig. 5 HRC ΔL (despace) vs temperature.

location.[1] The end rings roll away from the housing cylinder (increasing axial spacing at the outer diameter of the ring) because of the large CTE of the gr/ep perpendicular to the planes of the plies. This causes the mirrors to register on the inside diameter (which has little axial despace) below room temperature or to register on the outside diameter (which has large axial despace). In order to correct the high CTE above room temperature, we lapped portions of the ULE pads that mate the parts so that the mirrors always should register on the inner ring diameters. The thermal despace data taken after the partial lapping of the ULE pads is shown in Fig. 5. Figure 5 (with an average CTE of $0.045/10^6$ in./in./°C) shows that the (relatively) large axial descape above room temperature was corrected by partially lapping the ULE pads. This cycle of initial test data, finite-element analysis, ULE pad lapping, and subsequent test data helped demonstrate how gr/ep structural design has to be tailored for the specific application.

Telescope Testing Conclusions

The empirical results presented in this paper show that a gr/ep housing and gr/ep secondary spider, along with ULE mirrors, can be used to assemble a 6-in. telescope that meets 1 arcsec boresight shift and 1-mil defocus requirements. These results, being published for the first time, show that gr/ep structures can be used along with ULE mirrors to build thermally insensitive telescopes. One important contribution of this work is to show that gr/ep and ULE telescope assemblies can be used practically, to meet requirements of thermally insensitive 6-in.-diam star sensors, star trackers, and radiometers. The orientation of the gr/ep plies is picked to meet the individual design requirements. Thus each requirement leads to a tailored design. These results can lead to thermally insensitive sensors that could have $<<1$ arcsec pointing errors and replace metallic (housing) sensors that have >4 arcsec pointing errors. The data presented in this paper show that a 6-in. gr/ep and ULE telescope, which is relatively thermally insensitive, is a state-of-the-art contribution vs thermally sensitive metallic telescopes.

Summary

This paper has presented design requirements and test data of a gr/ep and ULE telescope. The test data show that the required telescope and coefficient of thermal expansion of $\leq 0.05/10^6$ in./in./°C and thermal tilt sensitivity of <0.9 arcsec/°C (of thermal diametral gradient) were met. These results provide data for evaluating feasibility of designing and qualifying gr/ep and ULE telescopes for applications requiring thermally insensitive telescopes.

References

[1]Dunbar, D.R., "Star Tracker Telescope Thermal Distortion Analysis," GD/Convair Aerospace Div. Letter 646-0-76L-006, Jan. 19, 1976