Development of a carbon fibre composite active mirror: 
Design and testing

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Abstract

Carbon fibre composite technology for lightweight mirrors is gaining increasing interest in the space- and ground-based astronomical communities for its low weight, ease of manufacturing, excellent thermal qualities and robustness. We present here first results of a project to design and produce a 27 cm diameter deformable carbon fibre composite mirror. The aim was to produce a high surface form accuracy as well as low surface roughness. As part of this programme, a passive mirror was developed to investigate stability and coating issues. Results from the manufacturing and polishing process are reported here. We also present results of a mechanical and thermal finite element analysis, as well as early experimental findings of the deformable mirror. Possible applications and future work are discussed.
1 Introduction

The last decade has seen a substantial effort to develop ultra-lightweight optics for imaging systems. Research has been strongly driven by the aerospace industry, where the weight of the payload directly influences the cost of a mission or craft. The advent of the James Webb Space Telescope (JWST) in particular has invigorated the research drive [1]. In astronomy too, where instruments and telescopes have dramatically increased in size and complexity over this period, using lightweight optics allows decreased tolerances for support structures, which can again save substantial cost as well as reduce maintenance requirements for the telescope.

Several methods exist for reducing mass of traditional optical materials, such as Zerodur and Beryllium, by material removal [3]. Lightweighting conventional low thermal expansion glass mirrors is however expensive and there is considerable variability in the time taken to produce and polish glass items, and limitations of material suppliers - all of which increase programme risks. Beryllium is also toxic and requires very strict safety precautions during the manufacturing process. Much progress has been made in recent years in developing novel materials for lightweight optics, both for space and terrestrial environments - including carbon fibre-reinforced silicon carbide (CeSic) [4] and sintered silicon carbide (SSiC) [5].

Carbon fibre composite (CFC) materials offer an attractive alternative, being very robust whilst relatively easy (and cost-effective) to manipulate. Because of their composite nature the material properties can be tailored to a specific application, thus making them very versatile. They also exhibit near-zero thermal expansion. Table 1 shows a comparison of typical material properties for CFC and other mirror materials. In general, composite structures are manufactured using a moulding process. Plies of fibres in a raw resin material are deposited onto a mould or mandrel together with a curing agent. Heat and pressure are then applied, eventually resulting in a 'quasi-isotropic' laminate.

However, for use in the optical wavelength regime, several problems still remain to be overcome, one of which is the surface roughness. Carbon fibre composites can not be polished directly. To achieve a good surface roughness, replication techniques must be used using high optical quality moulds or the composite must be coated with a polishable material. Mirror form error presents another problem. Because the curing process takes place at elevated temperature, there are issues with the overall form on release from the mould.

Several research projects into carbon fibre composite mirrors (both active and passive) are ongoing [6, 7], particularly in the United States, focused largely on producing ultra-smooth surfaces using replication techniques. This work is important, as ease of replication can significantly speed up the production process when a large number of optics is required, as well as cut
costs. For a high-quality optical system, however, a good form is also required. If actuators are used to control the mirror’s shape, tolerances can be decreased as low-order shape distortions can be compensated - but if part of the actuators’ stroke is required to flatten the mirror this will decrease their ability to compensate for other optical effects.

An alternative approach is to coat the mirror with a material that can be ground and polished. The advantage of this is that the tolerance on the production of the CFC mirror from the mould are reduced as the substrate can be ground to the required form either before or, if sufficient coating material is applied, after the coating process (see, for example, [2]). This paper will describe in detail the first results from a project carried out at University College London (UCL) in collaboration with industrial partners QinetiQ and Cobham Composites to develop a prototype deformable CFC optical mirror using this approach. The aim of this project was to investigate the production methods and to test key performance parameters, such as mirror influence functions and form errors. The following sections will describe the results from a passive test mirror, design of the prototype active mirror, potential applications and future work.

2 Design considerations

The ultimate aim of a deformable mirror for active or adaptive optics is an ability to correct any aberrations originating in the atmosphere or within the optical system itself. These aberrations can arise from changes in the gravitational or thermal environment in the case of a space-borne system, or from gravity sagging or atmospheric turbulence for ground-based systems. For the CFC active mirror, the design was driven by several considerations. The baseline specifications (Young’s modulus, stiffness, actuator spacing) were made to match that of a previous deformable mirror system that was developed at UCL in the late 1990s. This system is described in detail by Lee et al. [8] and Lee [9] and features an aluminium faceplate with a diameter of 27 cm, whose shape is controlled by 7 magnetostrictive actuators spaced at 10 cm in a hexagonal arrangement, plus full backing structure, drive electronics and software. Its form is concave and spherical, with a radius of curvature of 2945 mm. The mechanical design of the aluminium mirror resulted from a study by Bigelow et al. [10]. In addition, the CFC material dictated its own particular requirements.

The faceplate’s stiffness must be such that the inter-actuator sagging during both horizontal and vertical pointing is small. For a typical optical surface this is of the order of nanometres. Also, the forces executed on the structure by the actuators must lie within the interlaminar strength to avoid cracking and delamination.
Because CFC is intrinsically non-reflective, a nickel coating was added to the design, and this formed the biggest challenge to the project. Though the composite has an excellent thermal stability, the addition of a nickel layer was likely to introduce a mismatch effect with possible mirror stresses and distortions as a result. Finite element analysis (FEA) results indeed supported this prediction. The thickness of the nickel layer also was to be balanced against the requirements for polishing and grinding in the post-production phase.

Another important question mark hangs over the mirror’s stability through varying humidity regimes. As shown in table 1, CFC has a non-zero moisture expansion coefficient. The exact value depends on the matrix material used, e.g. a normal space-qualified epoxy has a CME of around 25 parts per million (ppm) (for a fibre volume fraction of 0.6) whereas a cyanate ester resin’s is just 9-10 ppm, albeit at 3 times the cost. Little information is available on how the material’s moisture absorption affects its strength or shape; as with many aspects of carbon fibre materials, the effect is poorly quantified. This was hence not a major influence on the proposed design but the mirror’s stability was closely watched during testing. Care was taken to avoid moisture uptake by the substrate during polishing by sealing the mirror edge with a lacquer coating.

To investigate some of these issues and test the manufacturing and polishing methods, it was decided to produce a passive composite test mirror with the same size and radius of curvature. The actual laminate configuration for this mirror was stiffer than the active design as its shape was not intended to be actively controlled. Such a mirror could be of use in space applications where active control is beyond the mission’s scope.

3 Passive test mirror: Design and testing

3.1 Preliminary FEA results

For the passive mirror, a sandwich plate design was decided on from the outset to make optimal use of the composite’s low weight and thermal expansion properties. Commonly used in composite manufacturing, a cored lay-up has the advantage of providing extra stiffness to the laminate without adding significantly to its weight. For this particular purpose, an aluminium alloy honeycomb was chosen, as these are cheap, widely available, easy to manipulate, and have a very good strength-to-weight ratio.

Finite element analysis was then carried out to predict the amount of gravitational sagging to be expected from laminates with different core thicknesses. Initial modelling was carried out
at QinetiQ using Ansys/Nastran, later reconfirmed by further work at UCL presented here, using I-Deas. The mirror itself was modelled using 2D thin shell elements. The laminate was constructed using the Laminates tool in I-Deas, which uses the material properties of individual plies to compute equivalent orthotropic properties for the laminate. Using this method the laminate thickness is automatically translated to the 2D elements. Preliminary tests showed that individual ply thickness or stacking sequence - providing the ply balance and symmetry was respected - did not have a significant effect on resultant material properties.

Three different support methods were modelled: an edge support round the entire diameter, a 3-point support at the mirror edge, and a 7-point support. In the 7-point support model, nodes within a circular area of diameter 25 mm were coupled and restrained at the proposed actuator locations, to simulate the effect of an actuator pad. The reason for including this configuration was to enable an easy comparison with earlier FEA results for the aluminium active mirror, upon which the design was based. For a passive mirror an edge or 3-point support would be more realistic. The approximate restraint method was used to save on computing time; to include a full model of actuators attachments would have increased the solve time significantly. Table 2 summarizes the results for rms gravitational sag for various core thicknesses. Figure 1 shows a plot of gravitational sag results from FEA for the 10 mm cored model with 7-point support. A similar FEA model of the aluminium active mirror [9] showed a maximum zenith-pointing sag of 31.9 nm. The 10 mm cored model matched this value very closely with a maximum sag of 33.4 nm and this lay-up was therefore chosen for the test mirror.

Thermal FEA on the 10 mm cored model yielded a predicted defocus of 16-17 mm for a 100\(\mu\)m nickel layer for \(\Delta T = +10^\circ C\), reducing to just 5 mm if the layer is reduced to 25\(\mu\)m. Models also showed that a matching nickel layer on the mirror’s back surface would virtually eliminate the effects of this mismatch. However, the manufacturing modifications required for this were not part of the project’s aims.

### 3.2 Design and initial form

During the manufacturing phase carried out by Cobham Composites a nickel coating was transferred onto the mirror from the mould. A picture of the mirror prior to grinding and polishing is shown in figure 2. The coating thickness was overspecified in the first instance to ensure that enough material was available for grinding and polishing; experience with the test mirror could indicate whether it could be reduced to minimise any bimetallic effects.

Before grinding and polishing the most marked feature on the mirror’s surface was a fibre print-through. The origin of this was uncertain as print-through was not expected through a
100 µm thick layer of metal. Following discussion with the manufacturing team it was suggested that the features were due to post-cure shrinkage of the adhesive layer between composite and nickel that ‘pulled’ the nickel around the underlying fibres. Also present were uni-directional striations across the reflective surface spaced around 1 cm apart, and a ring-shaped depression approximately 2 cm inside the mirror edge. Figure 3 shows a profilometry measurement with a Mark 1 Form Talysurf before grinding and polishing. This measurement shows form errors of approximately ±5µm from a spherical form. The ring feature can be seen as the first valley in the plot. After an investigation of the materials used it appeared that a filler material had been used along the edges to protect the aluminium core from crushing under the vacuum bag pressure during the lay-up process. The cause of the striations was not conclusively identified.

Interferometry testing revealed a radius of curvature of 2910 mm - 35 mm shorter than that of the mould - indicating that residual stresses on release from the mould had increased the mirror’s concavity. This can almost certainly be attributed to stresses caused by the thermal expansion mismatch between the nickel and composite on cooling. Indeed, a composite-only test sample made with the same mould did not show this level of radius of curvature shrinkage.

3.3 Final surface, form and testing

The mirror was ground and polished manually by D. Brooks using polishing tools of up to 7/8 of the mirror size. The edges were protected against moisture ingress from the polishing slurry. The mirror was supported on a compliant layer whilst being polished to prevent the introduction of further stresses. After successive cycles of grinding, polishing and measurement, a surface roughness of 4 nm was obtained, measured over a 1mm² square. This value is no absolute limit and can be improved on with experience. The striations and fibre print-through observed after the lay-up were removed in the polishing process.

Figure 4 shows the final mirror form. The interferogram clearly shows a residual edge depression that was not removed by the grinding process. The overall surface form was 1µm P-V, the edge ring accounting for a large part of this. The central 24 cm displayed a form of 517nm P-V. Apart from the bimetallic effect, another possible cause of these form errors is a slight misalignment of ply angle within the composite laminate, which could affect its stability. Figure 5 shows a picture of the passive mirror after polishing.

The mirror displayed no measureable form changes over one month at constant temperature and relative humidity. Its long term stability remains under investigation. A thermal stability test showed a defocus of 6 mm for ∆T = 5°C. The magnitude of this is in good agreement with FEA results.
4 Active mirror design

From experience with the passive mirror, it was clear that the main problem with a nickel-coated active mirror was likely to be the thermal stability. Flexures were included in the design to relieve any stresses. The amount of actuator stroke used to flatten the mirror should be kept to a minimum so efforts must be made to obtain the best possible form before flattening.

The key property that defines how a material will respond to actuation (in terms of stroke and influence function shape) is its specific stiffness, defined as $E/\rho$, with $E$ the Young’s modulus and $\rho$ the material density. A higher specific stiffness increases the actuator coupling and avoids a ‘dimpling’ effect of the faceplate, but also increases the required power for a given stroke, and hence also the dissipation, which can be a critical factor.

Because of the relatively large actuator spacing of 10 cm and to counter the bimetallic effect, the composite was stiffened with an aluminium honeycomb core, as with the passive test mirror. In this case, however, the core thickness was just 4 mm and no core filler was used to avoid the edge effects encountered previously. Similar FEA models were carried out to those describe in section 3.1. For the chosen laminate these revealed an rms gravitational sag of 150 nm with the mirror pointed in the vertical direction and the actuators modelled as points, as before. The mirror was manufactured by Cobham Composites and delivered to UCL late in 2004, for grinding, polishing and testing. On delivery it weighed 312 g (see figure 6).

Initial interferometry testing showed that the mirror showed a degree of astigmatism (65$\mu$m) and again some print-through from the fibres. Grinding and polishing reduced the former to 15$\mu$m and eliminated the fibre print-through. No edge ring was observed, suggesting that the team’s assessment of the feature in the passive mirror was accurate. At the time of writing the mirror was being prepared for active testing. The magnetostrictive actuators will be connected to the mirror faceplate via circular pads of 25 mm diameter to reduce any ‘top-hat’ effect in the influence functions. A low-shrinkage (less than 1%) glue suitable for use with composite materials was selected for this purpose. The aluminium backing structure provides extra stiffness and a reference for the actuators. Figure 7 shows a schematic of the active mirror setup. Further stability testing will also be carried out.

5 Conclusions

Experience with carbon fibre composite optical elements remains limited, and many problems will need addressing before the technology can become routinely implemented. The work de-
scribed here has answered many questions and highlighted some of the major issues.

The passive prototype has shown that a spherical surface can be produced with form errors of the order of $10\mu m$ for a 'thick' CFC mirror design. These errors are suspected to arise from residual stresses at the nickel-CFC interface or misalignment of plies within the laminates. However, grinding and polishing reduced the form errors substantially. A very good surface quality (4 nm Ra) was achieved with conventional manual polishing, and this can certainly be improved with experience. The fibre print-through that was initially seen on the nickel surface was also removed. The laminate was shown to be very robust, with minimal delamination around the mirror’s edge following substantial working. Thermal tests showed a distortion of the surface with changing temperature, particularly in the form of defocus as predicted by FEA modelling, but this instability could be resolved by coating the mirror’s back surface with a matching nickel layer.

Testing of the active mirror shows some residual astigmatism after grinding and polishing. The form error, however, remains well within the actuator stroke so should not affect the ability the flatten the mirror.

The cause of the residual form errors observed in both these mirrors will have to be investigated and the manufacturing, grinding and polishing processes refined accordingly. However, the initial results are promising nonetheless. In the months to come, the deformable mirror will be tested for its active performance and these results will be discussed in detail in further publications.

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Sarah Kendrew has been studying at University College London (UCL) since 1997, gaining an MSci. in Astronomy in 2001. She is currently studying for a PhD on lightweight deformable mirrors with Dr. Peter Doel as a member of the Optical Science Laboratory.
Peter Doel has been a lecturer at University College London since 1998, where he is involved in research in adaptive optics systems and astronomical instrumentation. Prior to UCL he was a member of the Durham Astronomical Instrumentation Group as a postdoctoral research assistant from 1990 to 1998. He obtained his PhD at Durham University in 1990.

David Brooks joined the Optical Science Laboratory at UCL in 1985, gaining a PhD in 2001. He is responsible for optical manufacturing, metrology and testing in the group.

Chris Dorn is a general and systems engineer with 15 years of experience in the space industry. He has worked on several missions from design to operations, including Earth observation and spaceborne astronomy. Currently the leader of the Specialist Missions Team in QinetiQ Space Division.

Chris Yates has spent over 18 years in finite element modelling for real systems. Initially involved with modelling of transportable bridges for Army bridging systems, he has worked on space-related projects at QinetiQ for the last 8 years. His analysis has addressed both macro-scale issues associated with large solar arrays and the micro-scale issues of optical systems.

Richard Dwan is a Theoretical Physics graduate from Durham University and during his time there he had strong links with the adaptive optics group based at Durham. In 2002 he joined QinetiQ’s space department and has been involved with a wide range of reflective optical and infrared systems.

Ian Richardson joined Cobham Composites in 1994. He is the Sales Director for this company and the wider Chelton Composites Group. Previously he has held various research positions covering the development of high strain and high modulus PAN based carbon fibres and their interaction with toughened epoxy matrices. He has over 25 years experience in composite materials.

Glynn Evans is a mechanical engineer with more than 20 years’ experience in the aerospace/composite materials industry. Since 1997 he has been the Engineering Manager at Cobham Composites.
| Material   | Density (kg/m³) | Young’s modulus (GPa) | Specific stiffness (N.m/kg) | CTE (ppm/C) | CME @ 35%RH |
|------------|----------------|-----------------------|-----------------------------|-------------|-------------|
| Aluminium  | 2710           | 71                    | 26.2                        | 23.9        | 0           |
| Zerodur    | 2520           | 92.9                  | 36.9                        | 0.05        | 0           |
| SiC        | 3140           | 420                   | 133.8                       | 2.2         | 0           |
| Cesic      | 2650           | 220                   | 83                          | 2.0         | 0           |
| CFC        | 1170           | 101                   | 86.3                        | 0.2         | 9.0-25*     |
| Beryllium  | 1850           | 300                   | 162.2                       | 11.5        |             |

Table 1: Typical key material properties. CME: coefficient of moisture absorption. * CME of CFC material is strongly matrix-dependent [12, 11, 13].

| Core thickness | 3-point support | 7-point support | edge support |
|----------------|-----------------|-----------------|-------------|
| 5 mm           | 895.5 nm        | 34.3 nm         | 75.9 nm     |
| 10 mm          | 522.7 nm        | 20.6 nm         | 43.3 nm     |
| 15 mm          | 378.3 nm        | 15.1 nm         | 31.2 nm     |

Table 2: FEA results for rms gravitational sag of the passive carbon fibre composite test mirror for various core thicknesses. The 7-point support used 25 mm diameter pad-shaped restraints to simulate the actuation pads.

Figure 1: Gravity sag FEA results for the passive mirror with a 10 mm core and 7-point support as described in section 3.1. The central pad restraint is slightly oversized, this is due to the layout of the nodes in that part of the mesh. This did not significantly affect the rms of maximum sag values.

Figure 2: Passive test mirror during the grinding process.

Figure 3: Profilometry measurement of outer 10 cm of the mirror face, showing the structure of depressed ring around 30 mm inside the edge with a magnitude of 10μm.

Figure 4: Interferometry measurement of the passive test mirror form after grinding and polishing.

Figure 5: Picture of the passive mirror after polishing.

Figure 6: Active mirror pre-grinding

Figure 7: Active mirror setup