ARCUATE ARM PROFILOMETRY - TRACEABLE METROLOGY FOR LARGE MIRRORS

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Abstract: The next generation of ground-based extremely large telescopes of 30 m to 100 m aperture calls for the manufacture of several hundred mirror segments of 1 m to 2 m diameter. Manufacture of these segments requires a systematic approach to in- and post-process metrology for all stages of manufacture. To address the need for measurements on such 1 m to 2 m telescope segments, a swing-arm profilometer has been constructed as part of a collaborative project between University College London (UCL) and the National Physical Laboratory (NPL). The current swing-arm profilometer is intended as a proof-of-concept device, designed to measure concave and convex surfaces of up to 1 m in diameter with a minimum radius of curvature of 1.75 m for concave and 1.25 m for convex surfaces. It will be used to investigate metrology issues associated with the measurement of large aspheric surfaces. Principles of the swing-arm instrument are described together with the mechanics of the arm design, its bearing and adjustment arrangements and surface probe options. Some example measurement results are shown and some ideas towards the next generation measuring instrument are described.

1. INTRODUCTION

Amongst the latest applications areas considering the use of precision aspheric surfaces, perhaps the archetypal example is the use of segmented, aspheric panels to form the primary mirrors of the next generation of ground-based extremely large telescopes (ELTs). These telescopes require primary mirrors of 30 to 100 m diameter, constructed from hundreds of segments, each segment being typically 1 to 2 m diameter. For example the Euro 50 telescope [1] plans to use 618 hexagonal segments, each 2 m diameter, to construct its 50 m diameter primary mirror. Each panel segment will have a designed asphericity ranging from 3 to 300 µm, and will require machining to a form tolerance of 36 nm RMS. The segments also need their radii of curvature, which are typically 85 m, matched to within 0.5 mm.

The efficient manufacture and maintenance of such a large number of segments to these small tolerances, places extraordinary demands on the manufacturing and metrology processes used at all stages, from initial grinding, to final testing and subsequent re-surfacing and re-testing. Techniques for mass fabrication of such segments are already under development [2, 3].

Traditionally, various metrology solutions have been used during the different manufacturing stages, ranging from classical linear axis profilometry during the grinding stages, to interferometric testing of the finished mirror. In order to cope with large asphericities, Fizeau interferometers, which are traditionally used on flat or spherical surfaces, have used nulling lenses or, more recently, computer generated holograms, to reduce the fringe density from highly aspheric slopes, to a level that can be imaged onto CCD detectors, without loss of fringe contrast. However, optical testing of large aspheric or spherical mirrors requires generation of precise spherical reference wavefronts, and this can be difficult to achieve for long radii of curvature, or over large apertures, due to air turbulence and refractive index effects.

Recent developments in large mirror metrology have included the use of swing-arm profilometers [4] for measurements during grinding stages. Such arcuate profilometers benefit from significantly reduced cosine errors with respect to linear axis profilometers (see §2), but can take a significant time to measure the surface in sufficient detail, due to the need to make many scans across the surface. Overall accuracy is also limited by the resolution and linearity of the probe used (typically an LVDT).

However, recent advances in wavefront sensing technology [5] have produced small sensors which could be mounted on a swing arm, replacing the usual contacting LVDT sensor with a non-contacting optical sensor. With a typical sub-aperture view of the surface of a few tens of millimeters diameter, optical wavefront sensors offer a more detailed view of the surface and can cover more surface area than a contacting probe, leading to reduced measurement times (see Fig. 1).

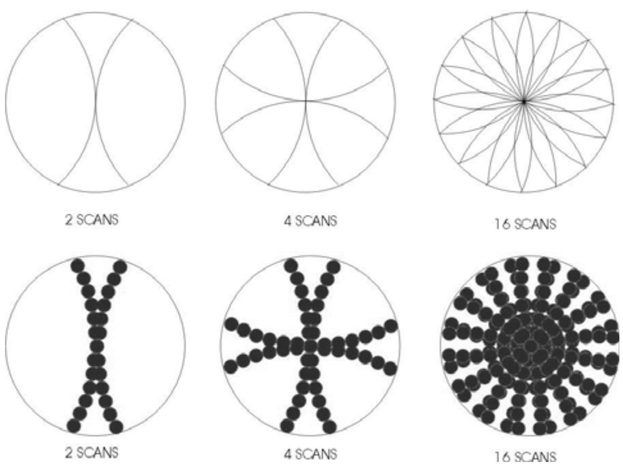

Fig. 1 *Comparing multiple scans with a contact probe (top) and an optical sensor (bottom).*

As a first step towards using swing arm profilometry for large mirror segments, the National Physical Laboratory (NPL) and University College London (UCL) have been collaborating on a project to design and build a prototype swing arm profilometer (SAP) for the measurement of optics up to 1 m diameter. The NPL/UCL swing arm profilometer has been specifically designed to allow the mounting of a selection of different probes, allowing different metrology solutions to be used during different stages of manufacture.

2. PRINCIPLES OF THE DESIGN

The outline schematic of the swing arm profilometer is shown in Fig. 2. A stiff arm is mounted onto a suitable rotation device, such that, as the device rotates, a probe attached to the and of the arm traces out a circle in space.

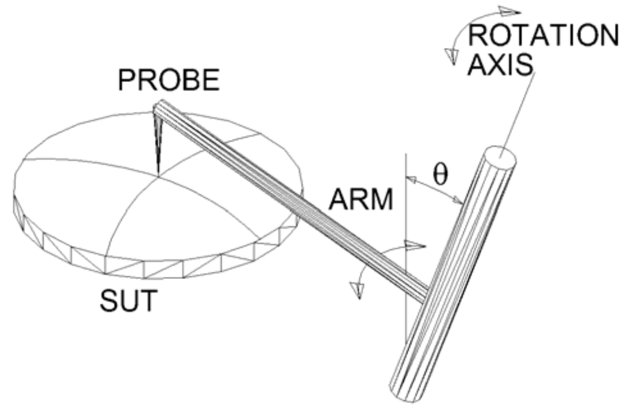

Fig. 2 *Swing arm profilometer schematic.*

If the tip of the probe is placed into contact with a convex or concave surface, and the rotation axis is accurately aligned and inclined with respect to the surface normal, then the probe tip will trace out an arcuate path that lies on a specific base sphere of the surface. The advantage of this arrangement is that the probe now only measures the departure from sphericity of the surface, rather than the absolute surface shape. For an optic with a short radius of curvature, but large diameter, this significantly reduces the accuracy requirements of the probe as it only requires a range large enough to cope with the departure from sphericity, rather than coping with the departure from flatness. For a typical Euro-50 mirror segment, the asphericity will be only 30 to 300 µm, whereas the sag at the centre (departure from flatness) is up to 10 mm. As well as reducing the accuracy requirement of the probe itself, the required alignment accuracy of the probe is reduced when the probe stroke length is decreased.

The necessary alignment is based on the tilt angle of the rotation axis, θ, the effective length of the swing arm, l, and the radius of curvature of the base sphere of the surface under test, R. A circle of radius l, where $0 < l < R$, can be orientated in space such that its periphery lies on the surface of the base sphere. The circle will remain along the surface, independent of the rotation of the sphere about the z axis, provided the axis of the circle intersects the centre of curvature of the sphere. The specific requirement is given by

$$\sin\theta = \frac{l}{R} \qquad (1)$$

However, the effective arm length, l, is difficult to measure or control, as it is a distance from the probe

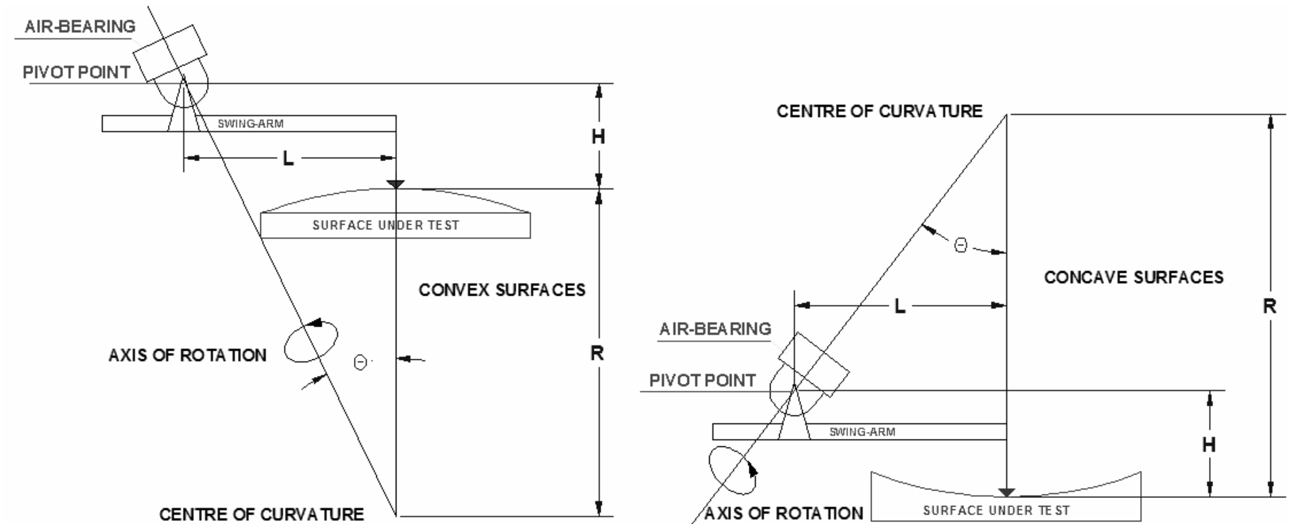

Fig. 3 *Swing arm profilometer alignment geometry.*

tip to a virtual line through the rotation axis. Instead, it is easier to keep the actual arm horizontal (through use of trunnions) and to control the physical arm length *L*, and the height of the tilt axis, *H*, above the apex of the surface, as shown in Fig. 3. Then the alignment requirement becomes:

$$\tan\theta = \frac{L}{R \pm H} \qquad (2)$$

where the denominator in equation (2) uses a positive sign for convex surfaces and a negative sign for concave surfaces.

3. NPL/UCL SWING ARM PROFILOMETER

3.1. Construction of the profilometer

The NPL/UCL swing arm profilometer is shown in Fig. 4. It was built by modifying an existing Coordinate Measuring Machine. The original granite base and the *x-y* stage were retained, the *x-y* stage now providing a 400 mm travel, 0.1 µm resolution positioning system for the swing arm bearing mount, which replaces the original *z*-stage of the CMM. The arm is a 1220 mm length of rectangular section alumina tube, chosen for its stiffness and relatively low thermal expansion coefficient (*cf* steel and aluminum). The arm is mounted on a precision air bearing (Professional Instruments BLOCK-HEAD® 10R), chosen for its 25 nm axial and radial run-outs. The air bearing spindle is equipped with a Heidenhain rotary encoder with 0.36 arc sec resolution. Two stub axles are mounted on the sides of the air bearing, allowing it to be tilted via a side mounted bell crank mechanism driven by a micrometer. This allows adjustment of θ with sub-arc-second resolution. The surface under test is mounted on a rotary air bearing table, via a two-axis centering stage. Motion control of both air bearings is via DC servo motors with servo control and data acquisition performed in LabVIEW®. The instruments is housed in a temperature controlled laboratory.

Fig. 4 *The NPL/UCL swing arm profilometer.*

3.2. Probing options

The end of the arm features a simple breadboard plate, which allows mounting of different sensors. The weight of the sensor is compensated for by counterbalance weights on the opposite end of the arm. Initial testing has been with a Solartron LT12 linear encoder probe, and an Arden Photonics AWS-50 wavefront sensor is currently being trialled. The wavefront sensor uses a distorted diffraction grating to provide intra- and extra-focal wavefront imaging to allow the wavefront curvature to be determined.

4. RESULTS

So far, only the LT12 probe has been used. This probe was calibrated against a frequency stabilized laser using an NPL-designed Jamin interferometer system. The linearity of the probe was determined to be 1.4 parts per million over its 12 mm range.

Surface measurements have been made with the LT12 probe on a 640 mm diameter f/9.5 concave sphere, which has been previously measured using a phase-stepping interferometer to be spherical to $\lambda/4$ at 632.8 nm. The mirror, made from Pyrex glass, has a radius of curvature of 6098 mm. The standard steel probe tip of the LT12 has been replaced with a tip made from PTFE, to avoid surface damage.

The alignment process is iterative due to the cross-coupling between the various adjustment axes (x, y, z, θ of the arm pivot; x, y centering of the optic). After the optic was mounted on the rotary table, it was optically centered. Next, the swing arm tilt was adjusted until the profile of a test sweep across the surface was suitable flattened. Next the x-y position of the swing arm rotation axis was adjusted to coincide with the centre of curvature of the optic, leveling the trace. Further refinements were made to the tilt angle, θ.

Measurement scans were then made by moving the probe tip across the surface, and recording the probe deflection data at known sweep angles, using the Heidenhain scale in the arm bearing. For each scan, the arm is moved to a start position at –20 ° sweep angle (φ) where the probe is zeroed. The arm is then accelerated to a rotational speed of 0.02 rpm and the probe scans over the surface, decelerating to reach the end position at +20 ° sweep angle. In each scan, the zero sweep angle corresponds to the probe being at the optic's vertex.

The results of ten repeated scans are shown in Fig. 5. The data are noise filtered using a 10 point moving average and residual tilt has been removed in post-processing. Repeatability of the measurement process is better than 30 nm. The increased noise evident towards the right in Fig. 5 is due to arm vibration during motion.

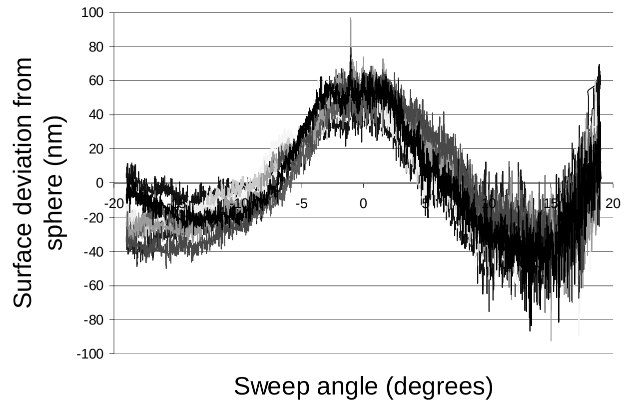

Fig. 5 *Ten repeat scans of 640 mm diameter concave spherical mirror with tilt removed and 10 point averaging filter applied.*

Fig. 6 shows a point by point average of the ten scans, with no filtering applied. The calculated RMS surface deviation along the scan is 28 nm, quite similar to the value of 40 nm obtained by the phase-stepping interferometer.

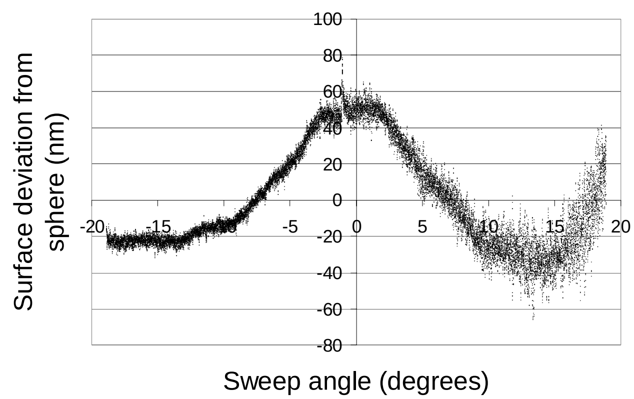

Fig. 6 *Point by point average of the scans in Fig. 5.*

Following the repeated scans shown in Figs. 5 and 6, several scans were made with the optic rotated 30 ° (α) between successive scans. These scans are depicted in Fig. 7, after being joined at φ = 0. Levelling of the individual scans can be performed using results from several concentric circular scans, made by fixing the arm position and rotating the optic, however the full set of scans depicted in Fig. 8 is only corrected for piston and rotation. Transformation from (α, φ) coordinates is made in software, using knowledge of L and θ.

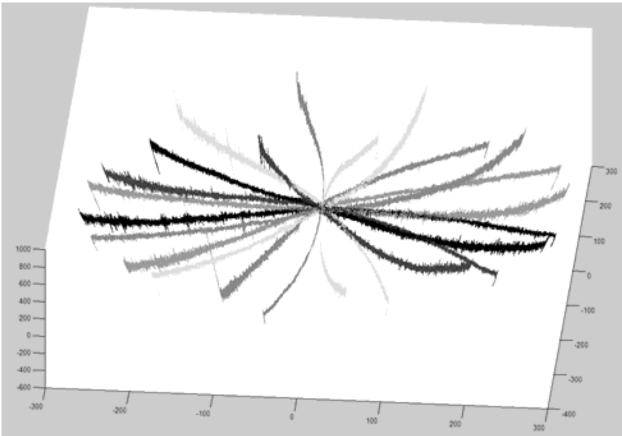

Fig. 7 *Scans at 30 ° rotation increments of optic, showing deviation from sphericity.*

The results of the stitched scans are in good agreement with the measurements made using the phase-stepping interferometer – the mirror surface is shown to be mostly spherical, with some astigmatism.

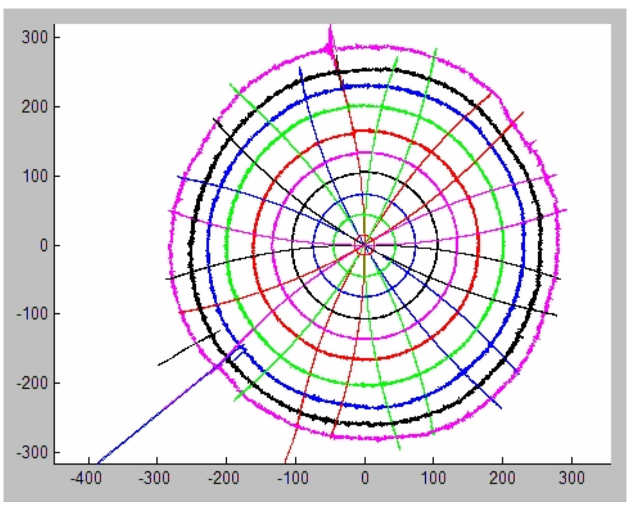

Fig. 8 *Scans at 30 ° increments plus 10 circular scans used for levelling – plan view.*

5. CONCLUSIONS & DISCUSSION

A prototype swing arm profilometer has been constructed by NPL & UCL and the performance of the instrument has been verified by measurement of a large spherical optic. The NPL/UCL swing arm profilometer can measure flats, concave and convex surfaces up to 1 m diameter with minimum radii of curvature of 1.75 m and 1.25 m, respectively. Repeatability of 30 nm and 28 nm RMS surface form deviation has been demonstrated on a spherical optic.

The next steps are to mount the wavefront sensor on the arm to allow larger sub-aperture measurements to be made and to provide some immunity to arm vibration. The data from the wavefront sensor swing arm will be used to estimate the likely measurement uncertainty and measuring time that could be achieved on larger optics for use in ELTs.

The next generation of swing arm profilometer will need additional metrology to allow the measurements to be traceable at lower uncertainty levels - at present the tilt angle, θ, and the arm length, L, are not measurable to sufficient accuracy for the requirements of ELT segment metrology. Laser interferometry is a potential solution to this.

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DISCLAIMER

The listing of any commercial equipment in this paper is not to be considered an endorsement by either NPL or UCL.

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