CYLINDER LENS ALIGNMENT IN THE LTP

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Cylinder lens alignment in the LTP

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ABSTRACT

The Long Trace Profiler (LTP) is well-suited for the measurement of the axial figure of cylindrical mirrors that usually have a long radius of curvature in the axial direction but have a short radius of curvature in the sagittal direction. The sagittal curvature causes the probe beam to diverge in the transverse direction without coming to a focus on the detector, resulting in a very weak signal. It is useful to place a cylinder lens into the optical system above the mirror under test to refocus the sagittal divergence and increase the signal level. A positive cylinder lens can be placed at two positions above the surface: the Cat's Eye reflection position and the Wavefront-Matching position. The Cat’s Eye position is very tolerant to mirror misalignment, which is not good if absolute axial radius of curvature is to be measured. Lateral positioning and rotational misalignments of lens and the mirror combine to produce unusual profile results. This paper looks at various alignment issues with measurements and by raytrace simulations to determine the best strategy to minimize radius of curvature errors in the measurement of cylindrical aspheres.

Keywords: Long Trace Profiler, LTP, profilometry, alignment, aspheric optics, metrology

INTRODUCTION

The Long Trace Profiler (LTP), a variant of the pencil-beam interferometer of von Bieren, was developed specifically to measure the slope error and figure of long cylindrical aspheric mirrors. These mirrors are often used in synchrotron radiation (SR) beam lines to collimate and focus x-rays at extreme grazing incidence angles. With source and image distances on the order of tens of meters and grazing incidence angles of a few tenths of a degree, the highly astigmatic surfaces generally have a major radius of curvature in the kilometer range, with a minor radius in the several centimeters range. These mirrors are often used in benders that change the major radius to focus or collimate a variable distance source or image. It is very difficult to measure the surface shape on these mirrors with conventional interferometers. Various scanning profilers have been developed to meet the metrology challenge posed by these surfaces.

In manufacturing a steep cylinder mirror, or in bending it to a specific radius, one needs to know the precise value of the major radius of curvature. A profiler measurement can provide this information, provided the scan axis of the profiler is aligned exactly parallel to the symmetry axis of the cylinder mirror. If the cylinder mirror is misaligned with some small rotational error, it is possible to couple a small fraction of the minor radius into the measurement of the major radius, thus resulting in an erroneous estimate for the major radius. One technique that can be used to quantify the amount of rotational alignment error is to make a series of scans with known rotation angle increments added to a baseline scan. The perfectly aligned case would correspond to the extremum in the derived radius value. This is, however, a very tedious and time-consuming measurement procedure. A cylinder lens is also used in some optical profiling instruments, such as the LTP, to reduce the defocus in the probe beam at the image plane. This element introduces additional degrees of freedom into the alignment problem and creates additional sources of error. This note examines the alignment tolerances required for accuracy in the measurement of cylindrical surfaces with profiling instruments and discusses methods for minimizing the error when measuring with the LTP.

MIRROR METROLOGY GEOMETRY

In analyzing the effect of alignment errors on the measurement of cylinder parameters by profilometry, it is useful to consider the more general case of the surface as a toroid with a large major radius. The relevant parameters defining a "bicycle tire" toroid, shown in Fig. 1, are the major radius, R, and the minor radius, ρ. A cylinder mirror can be thought of as a limiting case of a toroidal mirror when R \( \gg \infty \). The toroid is generated by revolving the center of a circle of radius ρ about the z-axis at a distance of R. The canonical equation for the toroidal surface in this coordinate system is...
The part of the surface used as a mirror in synchrotron beam lines is usually taken from the outside of the bicycle tire. At grazing incidence angles, the mirror becomes a long and narrow rectangular shape. Parameters for a typical toroidal mirror used in the present study are: \( R = 1.2 \text{ km} \), \( \rho = 80 \text{ mm} \), length \( L = 600 \text{ mm} \), and width \( W = 100 \text{ mm} \). In the metrology laboratory, the surface is more conveniently viewed in a translated and rotated coordinate system; where the origin is at the pole of the surface (lowest point at the center midpoint), the \( x\)-\( y \) plane is tangent to the pole, and the height of the surface above the \( x\)-\( y \) plane is measured in the \( z \)-direction. The transformed coordinate system is shown in Fig. 2. In this system, the equation for the toroid becomes:

\[
\rho^2 = \left( R - \sqrt{x^2 + y^2} \right)^2 + z^2. \tag{1}
\]

Since we are concerned only with small angular rotation errors about the local \( z \)-axis, we have \( x \gg y \) and since \( R \) is always much greater than any of the other distances, we can write this expression in terms of the profiler trace length \( x \) and the rotation error angle \( \theta \):

\[
z = \frac{x^2 \cos^2 \theta}{2R} + \frac{x^2 \sin^2 \theta}{2\rho}. \tag{2}
\]

For small angles, this reduces to

\[
z(x, \theta) = \frac{x^2}{2} \left( \frac{1}{R} + \frac{\theta^2}{\rho} \right). \tag{3}
\]

If the mirror is perfectly aligned, one can extract the design value of the major radius from the measured profile. If there is some rotational misalignment, Eqn. (4) shows that some fraction of the minor radius is coupled into the major radius value, resulting in the measurement of an effective radius of curvature, \( R_{\text{eff}} \):

\[
R_{\text{eff}} = \frac{R \rho}{\rho + R \theta^2} \tag{5}
\]

A more instructive interpretation results from writing Eqn. (4) in terms of the curvature instead of the radius:

\[
z(x, \theta) = \frac{x^2}{2} \left( C_R + C_\rho \theta^2 \right). \tag{6}
\]

or in terms of slope:

\[
z'(x, \theta) = x \left( C_R + C_\rho \theta^2 \right) \tag{7}
\]

In terms of the curvatures, one can see that for an ideal cylinder, with \( C_R = 0 \), any small angular misalignment will couple a significant amount of minor radius curvature into the measured result. In practice it is possible to align the symmetry axis of the mirror to the translation direction of the profiler to better than 1 mrad by eye. If this error were present in a measurement of our typical toroid, the misalignment would add a radius term of \( 80 \text{ km} \) to the nominal 1.2 km radius, resulting in about a 1.5% error in the measurement. In some cases this amount of error cannot be tolerated and needs to be minimized.

**CYLINDER LENS COMPENSATION**
Measurements on steep cylinder mirrors with pencil-beam optical probes suffer from loss of intensity due to severe defocusing of the return beam in the transverse direction. A simple solution to this problem in the LTP has been the addition of a cylinder lens into the test beam path to compensate for this transverse defocusing. The placement of the cylinder lens in the beam path is shown in Fig. 3. The axis of the cylinder lens is parallel to the axis of the surface under test (SUT). There are, however, two possible positions for placing the (positive) cylinder lens relative to the pole of the mirror surface: the Cat's Eye (CE) position, and the Wavefront-Matching (WM) position. Fig. 4 illustrates the location of each of these placements. The CE position places the lens at one focal distance above the surface, regardless of the radius of curvature of the mirror. The WM position places the lens so that its focal point is located at the center of curvature (CoC) of the mirror. Alignment of the SUT is extremely critical with the cylinder lens in the WM position. For the typical mirror parameters considered above, raytrace modeling of the WM configuration indicates that lateral translation of only 8μm is sufficient to move the laser beam laterally off the detector pixels. The CE position is much more forgiving for SUT misalignment. Raytrace modeling shows that the SUT can move more than 1.2mm laterally before the image begins to move off the detector. The CE position has been the preferred position for the cylinder lens because alignment is much easier in this case.

Pure lateral translation of the SUT produces only a lateral shift of the beam spot on the detector. It does not introduce any error along the direction of travel, which would be interpreted as a change in the surface slope. Rotational misalignment of the SUT does, however, couple a fraction of the minor radius curvature into the major radius direction, resulting in an error in the measured major radius. The analysis in the previous section was for an ideal system with no cylinder lens in place. It is not intuitively obvious how the cylinder lens would affect the apparent radius of curvature measurement with a misaligned SUT. The return beam reflected from the SUT would be sent through different parts of the cylinder lens as the surface was scanned, with the return beams wandering across the detector in both the lateral and axial directions. To investigate these effects, a systematic study of rotational misalignment was undertaken by both raytrace modeling and by scans with the LTP.
MEASUREMENT EXAMPLE

To verify the results of the raytrace calculations for SUT misalignments with the cylinder lens in place, a series of measurements were made on an uncoated Zerodur® cylinder mirror 600mm in length. The major radius, R, is nominally infinite; the minor radius, ρ, is 80mm. With the cylinder lens in the CE position, the mirror was aligned by eye to be parallel to the translation axis of the LTP probe beam to better than 0.5mm. Rotation of the mirror was effected by equal and opposite translation of each end of the mirror over a range of ±2.5mm for a total angular range of ±8.33mrad. Under these conditions, one would expect to see symmetry of the slope profiles about the centerline scan. Equal angles about the centerline should produce identical profiles. Results of the slope profile scans over this angular range are shown in Fig. 5. The centerline scan at θ = 0° is subtracted from each and the residuals are plotted in Fig. 6. Corresponding height profiles integrated from the residual slopes are shown in Fig. 7. One sees immediately from the residual slope and height plots that the scans are not as expected for symmetric rotations about the central scan. Plotting the height profiles in a 3D volume (Fig. 8) gives the appearance that the surface is twisted.

Fig. 5: Slope profiles measured as a function of mirror rotation angle. Angle is measured in terms of SUT end displacement in units of millimeters: 0.5mm = 1.66mrad.

Fig. 6: Residual slope profiles after subtraction of centerline scan. Negative angle rotations show little change between scans, while positive angles show effects of minor radius coupling.

Fig. 7: Height profiles integrated from measured residual slopes for cylinder mirror rotation.

Fig. 8: Height profiles viewed in 3D volume. Surface appears twisted.
MODEL RESULTS – CAT'S EYE POSITION

In order to see if other explanations for the observed slope profile asymmetry were possible, other than assuming that the surface is twisted, a raytrace model for the LTP optical system was generated using OptiCAD®. Simulation scans were done with the cylinder mirror SUT rotated over the same range of angles as in the actual LTP scans. The results of the simulation with the cylinder lens perfectly aligned in the CE position are shown in Fig. 9. One can see that the slope profiles are indeed equal for corresponding positive and negative rotation angles. Also, the magnitude of the extreme slope profile in the simulation is smaller than the measured slope by a factor of two.

Simulation runs were done next with rotation error added to the cylinder lens. This is a likely error source, since the placement of the cylinder lens in the probe beam path is done with no external fiducial references. The simulation plots for a lens rotation error of 0.5° are shown in Fig. 10. One can see immediately that the slope profile for the positive SUT angles become steeper and those for the negative SUT angles change sign and flatten out above the baseline scan, exactly like the measured data in Fig. 6. Other runs were made with lateral translation error added to the cylinder lens in addition to rotation error, but the results are completely insensitive to translation error of the cylinder lens in the y-direction. Thus, it appears that a cylinder lens rotational misalignment of only 0.5°, or about 8.5 mrad, is sufficient to reproduce the observed slope profile measurements.

MODEL RESULTS – WAVEFRONT-MATCHING POSITION

Precise alignment of the SUT with the cylinder lens in the WM position has always been difficult to achieve because of the insensitivity to SUT misalignment. For this reason the CE position has been favored to increase the image intensity on the detector focal plane. Measurements with the lens in the WM position indicate that SUT lateral alignment errors of only several tens of microns and rotational errors of only a few tens of microradians can be tolerated before the beam spot walks off of the detector active area. Model calculations confirm this behavior. Simulation scans with cylinder lens rotation and translation misalignments are shown in Fig. 11. Note that the range of SUT rotation misalignment is reduced to ±50 μrad in these WM simulations to keep the image from walking off the edge of the detector. Consequently, the slope error scale is significantly reduced for the perfectly-aligned cylinder lens case (left frame). When the cylinder lens is given some rotational misalignment, 1.0° (center frame), the apparent slope error introduced only reaches about 10 μrad at the extremes of the scan, which is much less error than in the extremes of the CE scans. In the more realistic case where the cylinder lens is both rotated and translated away from the probe beam optical axis (right frame), the total error range remains the same, but the absolute position on the detector is shifted due to the wedge angle introduced by the lens rotation (lowest order aberration).
DISCUSSION

The model calculations clearly show that it is difficult to precisely align the SUT cylinder mirror with the cylinder lens in the Cat's Eye position. The cylinder lens accommodates too well errors in rotation and translation of the SUT and also of the cylinder lens itself relative to the probe beam optical axis, keeping the interference fringes positioned somewhere on the detector for a wide range of misalignments. The CE lens position does not allow for a well-defined SUT alignment. The typical alignment technique of locating the scan centerline by measuring the beam spot position relative to the edges of the mirror with a ruled scale is only accurate to perhaps ±0.5 μm. This leaves the SUT misaligned by about 1 μrad. Combined with typical misalignment of the cyl lens, this misalignment magnitude could introduce apparent random slope errors of up to 100 microradians into the measurement (Figs. 9 & 10). In many cases this is an unacceptable error, as it would add too much error into the absolute radius of curvature value.

The Wavefront-Matching cylinder lens position allows the SUT to be positioned much more precisely than does the CE position. The extreme sensitivity to lateral misalignment guarantees that the SUT will be aligned to within 10 to 20 microns to the translation axis. However, even with the smaller rotation error tolerance on the SUT, errors in the alignment of the cylinder lens relative to the probe beam axis still produce apparent slope errors in the range of 10 microradians (Fig. 11). To reduce systematic errors from the cylinder lens to below the 1 μrad level, the lens would need to be aligned with the translation axis to better than 0.1°. This tolerance is unacceptable if the LTP is to be a useful, versatile metrology instrument for cylindrical aspheres.

Fortunately, based on the above model calculations, we can devise a measurement strategy that will guarantee that alignment-induced errors will be well below the instrumental measurement sensitivity. Fig. 12 shows the maximum possible error that can be introduced into a measured cylinder mirror aligned according to the following procedure:

1.) Place the cylinder lens in the CE position, roughly align the SUT mirror, and adjust the intensity and balance to get a good set of fringes on the detector.
2.) Move the cylinder lens up to the WM position and fine-tune the rotation of the SUT until the fringe intensity remains uniform over the entire length of the scan.
3.) Remove the cylinder lens and allow the return beam to diverge into the optical head. Readjust the intensity and balance controls until good fringe patterns are again observed on the detector.
4.) Record a set of axial scans.

Step 2 ensures that the SUT is aligned to within several microns of the translation stage axis, which corresponds to an angular error in the range of 10-20 μrad. Removing the cylinder lens in step 3 insures that the errors introduced into the measurement by cylinder lens misalignment are completely negligible. Simulation results shown in Fig. 12 with the cylinder lens removed indicate that an SUT misalignment of 50 μrad introduces only a maximum of ±10 μrad into the measurement, which is what is predicted by the analytic expression in eqn. 7.
This measurement procedure requires that the return beam reflected off of the SUT diverge unimpeded into the optical head. This will occur in the LTP with a corresponding decrease in fringe image intensity. In most cases, this loss of intensity can be adjusted by changing the balance and intensity controls on the optical head. In those instances when uncoated glass surfaces are being measured, it may be necessary to increase the detector integration time to boost the signal level.

CONCLUSIONS

Precise alignment of cylindrical aspheres is necessary in order to achieve accuracy in long radius measurements with the Long Trace Profiler. The use of a cylinder lens to mitigate the sagittal defocus produced by the cylindrical test surfaces introduces a new set of systematic errors into the problem. Raytrace modeling of typical component alignment tolerances shows that it is possible to minimize the error introduced into the radius measurement by following a specific alignment procedure. This procedure does not require extraordinary alignment tolerances in the cylinder lens positioning. The largest error introduced with this procedure for typical component parameters is in the range of 10nrad, which is well below the noise level for the present generation of LTP instruments.

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