

In-Situ Metrology and 3D Error Compensation for Precision Aspheres in Virtual Reality Viewing Optics

Neil Naples¹, Alex Sohn²

¹Precitech, Inc. Keene, NH, USA

²Reality Labs, Meta, Redmond, WA, USA

ABSTRACT

Pancake lenses [1] offer a path to more compact, high quality display systems for virtual Reality (VR) head-mounted displays (HMD's). As shown in Fig. 1, incorporating multiple refractions and reflections, these catadioptric optical systems require components with low surface errors when compared to more conventional refractive systems and are often thin due to weight constraints on HMD's. This makes their manufacture more difficult via direct diamond turning. Furthermore, for VR display optics, the mechanical aperture of a pancake lens is typically irregular to suit clearance of facial features and for aesthetics, leading to non-symmetric distortions imparted by holding forces. The proposed manufacturing process combines fast tool servo (FTS) turning with an in-situ, high-resolution chromatic confocal probe to perform 3D figure error compensation on one platform. By eliminating the need to remove the lens from the machine tool, and thus preserving its mounting location between process steps, the problem of repeatability via established datums is solved. Additionally, FTS machining provides the highest throughput possible, even after an axisymmetric surface inevitably becomes a freeform with 3D figure error correction applied.

BACKGROUND

Direct diamond turning of polymer lenses presents some unique challenges. Polymer materials exhibit a high coefficient of thermal expansion (CTE), tend to have a low modulus of elasticity and finished surfaces are easily degraded during processing due to low hardness. Precise temperature control

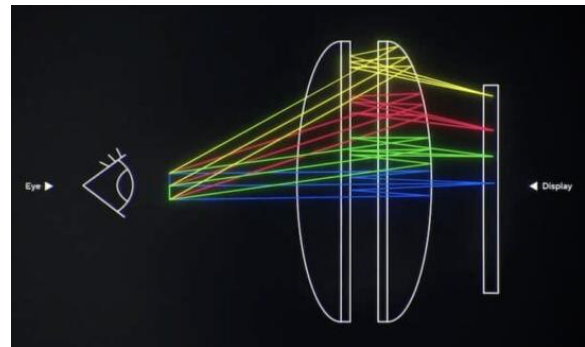


FIGURE 1. Pancake lens architecture combines reflective and refractive surfaces making for a more compact design but also more stringent surface tolerances. (Meta Platforms)

can alleviate the impact of thermal expansion errors, but low modulus is more difficult to address, particularly in low aspect ratio (thin) lenses. Any machining process depends on the ability to constrain the part during the material removal process; the applied holding forces must be enough to prevent the part from moving during machining. Furthermore, unconstrained regions of the part tend to vibrate leading to degraded surface roughness. One solution is to diamond turn an accurate vacuum chuck to constrain the lens during machining. However, even if the vacuum chuck may be perfect, the initial un-machined surface contacting it will not be, inevitably causing the part to distort. Careful management of vacuum forces can often be used to great advantage here, for example by lowering the vacuum during finish cuts. Unfortunately, lower vacuum force often results in the undeformed chuck surface losing contact with the mating part surface, leaving the part

to vibrate and resulting in degraded surface roughness.

An alternative solution is to diamond turn the part under high vacuum, let it distort, measure under minimal vacuum without removing the part from the chuck and then compensate for the errors in the measured shape in a re-cut. This can only be done well with in-situ metrology since the mounting will change, however subtly, if the part is removed from its machining fixture and limit the effectiveness of the compensation. Another advantage is that the entire process can be automated and thus be both fast and very efficient in terms of machine time and operator input. Finally, the issue of marring the diamond turned surface when the lens is reversed to finish the second surface, becomes much less of an issue since protective films can be applied without influencing the accuracy of the machining step.

PROCESS

In the proposed process, the lens in question is diamond turned in its deformed shape - fully constrained - and is then released during measurement by reducing vacuum to a bare minimum. The error measured with respect to the part datums (outside diameter and clocking flat) is then subtracted from the toolpath and, ideally, subsequent machining removes all the deformation errors. This process is limited only by the repeatability of the deformation and the accuracy of the measurement process.

A frequent objection to using in-situ metrology is that some common mode errors tend to be invisible if the same platform is used for both surface generation and metrology. In this case, the motion axes used are not all the same for both processes so most of these common mode errors are decoupled, and the rest can be removed by

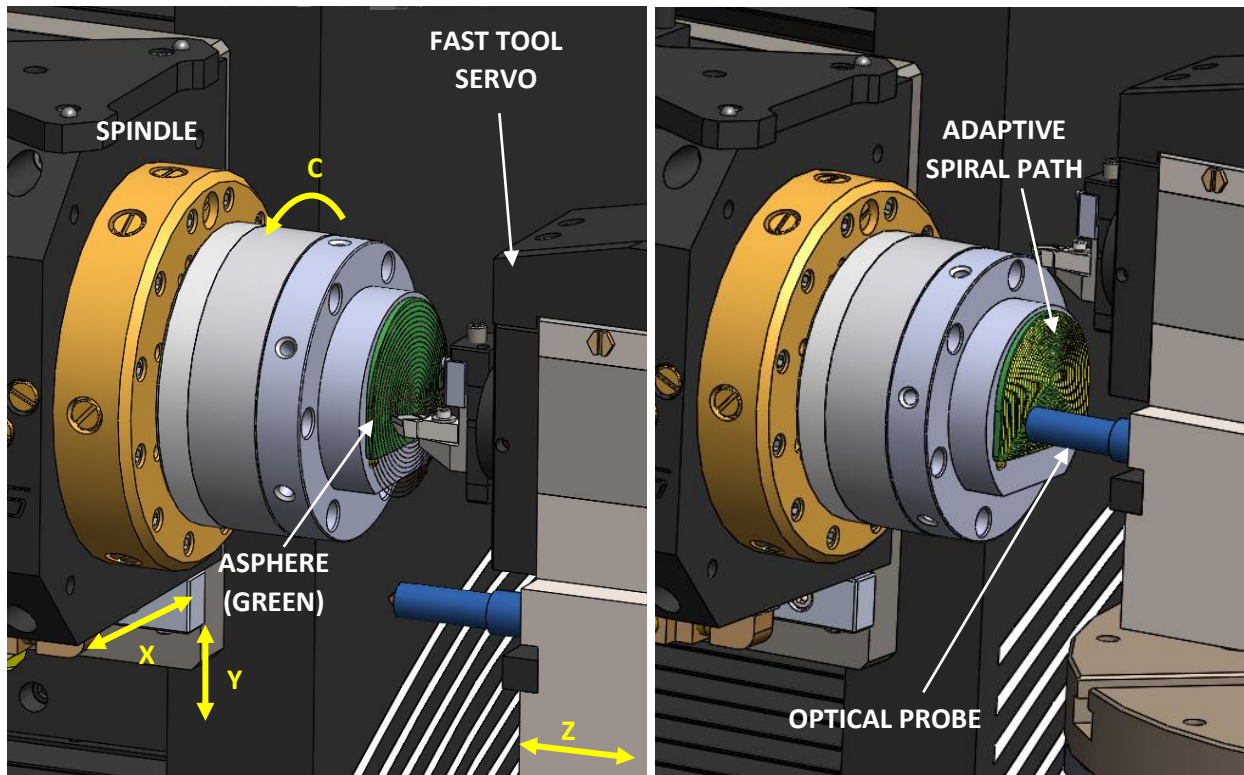


FIGURE 2. In-situ diamond turning (left) using XZC turning and metrology (right) using an XYZ adaptive spiral make rapid 3D compensation of form errors possible.

calibration. For example, the machining toolpath may be an XZC-spiral whereas the metrology toolpath may be an XYZ-spiral.

The process flow, illustrated in Fig. 2, is as follows: (1) Nominal toolpath generation: for the pancake asphere in this paper, the toolpath does not require extrapolation outside the part boundary because the surface is well-behaved in its region of interest; (2) Nominal diamond turning: since an asphere is axisymmetric, only an XZ-turning toolpath is necessary; (3) Initial in-situ metrology: the XYZ-adaptive spiral toolpath used is deliberately different from the machining toolpath because it is only necessary to measure inside the clear aperture of the surface, which in this case was irregular and equal to the part boundary; (4) 3D figure error compensation: due to poor fitting and extrapolation properties with traditional polynomials, a numerical fitting surface was computed via regularization. In this context, regularization is used to smoothly model noisy measurement data with respect to the established part datums. Additionally, the regularized surface exhibits well-behaved extrapolation between the part and toolpath boundaries. Briefly, regularized Z-values are computed by solving a large, linear system of equations with two main properties: smoothness and goodness of fit. Smoothness is achieved by setting the second derivative of the fitted surface at all XY-output grid points to zero. These second derivative terms act to 'stiffen' the surface and are why regularization extrapolates almost linearly in areas where there is no scattered data to locally deform the surface. Goodness of fit is achieved by mapping the XYZ-input scattered data onto the output XY-grid with cubic interpolation. Both properties are balanced with an adjustable scaling parameter that is equal to the ratio of smoothness to goodness of fit, allowing the fitted surface to take a form similar to a flat sheet of paper (higher smoothness), a

wrinkled sheet of paper (better goodness of fit), or anywhere in between. Because the system of equations is over-determined, it is necessary to solve via least squares. An angle of incidence error [2] correction could also be applied to the measured error in this step; (5) Compensated diamond turning: the same XZ-turning toolpath was used to machine the nominal asphere, but with the addition of a Fast Tool Servo (FTS) for machining the inverse of the regularized error into the part surface, thus removing the measured error from the part; (6) Final in-situ metrology: like step 2, an adaptive XYZ-spiral toolpath was used for this step because it differs from the machining toolpath; (7) Offline metrology verification. By design, the part is not removed from the machine during steps (1)-(6), removing the need to re-establish part datums between machining and metrology steps.

RESULTS

The PMMA pancake lens pictured in Fig. 3 has a center thickness of 4.9 mm and largest



FIGURE 3. Photograph of aspheric PMMA lens on vacuum chuck with asymmetric aperture. The measurement probe is the blue cylinder to the right.

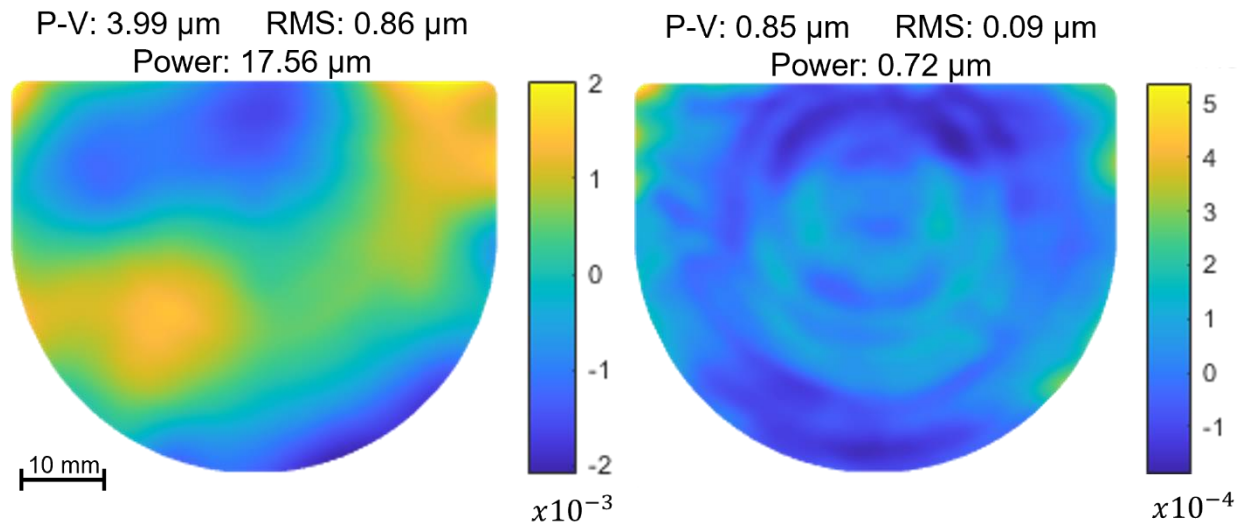


FIGURE 4. Pre-compensated error (left) was dominated by power at 17.5 μm and residual RMS error of 0.86 μm . Form compensation lowered these errors (right) to 0.71 μm and 0.08 μm , respectively. This represents a nearly 25x reduction in power error and 10x in residual RMS error.

aperture dimension of 59 mm, giving an aspect ratio of less than 1:12. Such thin lenses deflect significantly when held using vacuum. As shown in Fig. 4, after fitting the measured data to its aspheric prescription via translation and power, initial deformation error was dominated by power at nearly 18 μm and a residual RMS error of 0.86 μm . The proposed in-situ form error compensation process lowered these errors to 0.71 μm and 0.09 μm , respectively; a nearly 25x reduction in power error and 10x reduction in residual RMS error—a substantial improvement. Lastly, because the proposed process was used to measure net error with respect to the parts' datums, it not only compensates for mounting deformation, but also tool centering errors, tool radius and waviness errors, as well as any repeatable error that can be measured, regardless of source, including net shrinkage on a molded lens.

CONCLUSION

It has been shown that the described error compensation process can lead to significant improvements in surface figure errors in directly diamond turned lenses, particularly if

those lenses are easily deformed due to low structural stiffness or low material modulus. Integrating in-situ 3D non-contact profilometry into the manufacturing process of direct diamond-turned polymer lenses makes quick turn-around of high-quality aspheres and other components possible. The example illustrated in PMMA shows substantial surface figure error improvement and significantly improved cycle times over conventional error compensation via off-machine metrology. The process's ability to improve surface figure errors is limited only by the repeatability of the process and the accuracy of the probing system.

REFERENCES

1. David Heaney, "Breakthrough' Pancake Lenses Could Bring Compact Headsets", <https://uploadvr.com/kopin-all-plastic-pancake-optics/>, June 2021
2. Nouira, H., El-Hayek, N., Yuan, X. et al., "Characterization of the main error sources of chromatic confocal probes for dimensional measurement," Measurement Science and Technology 25(4), 044011 (2014)