Absolute Measurement of Rotationally Symmetrical Aspheric Surfaces

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Abstract: The surface is scanned along its symmetry axis in a Fizeau cavity with spherical reference surface. The coordinates x,y,z at the (moving) zone of normal incidence are derived from simultaneous phase-measurements at the apex and zone.

OCIS codes: (120.0120) Instrumentation, measurement and metrology; (220.0220) Optical design and fabrication; (120.3180) Interferometry; (120.4800) Optical standards and testing; (220.1250) Aspherics; (220.3740) Lithography; (220.4610) Optical fabrication; (220.4840) Optical testing.

1. Introduction

Aspheric surfaces, historically used mainly for astronomical mirrors, have now gained high importance in very different fields of optics such as pick-up lenses for CD, DVD and Blue Ray Discs, cameras in mobile phones, zoom-lenses for small digital cameras and camcorders, digital SLRs and Television Cameras, and especially, for lithographic projection lenses. The range of surface diameters spans more than two orders of magnitude for refractive optics, and the aspheric departure can be a few microns or as large as 5mm. The required uncertainty of the measurements can be as small as 0.1nm r.m.s., and the required spatial resolution as high as 2000 points across the diameter of the lens. Without a means to measure these surfaces, they cannot be manufactured!

In addition to uncertainty as a function of spatial resolution, other important factors to be considered are the cost for the measurement tool, the time required for one complete measurement (TACT), as well as the cost and lead-time for the "tools" to be manufactured before a measurement can be performed. Existing optical methods based on null compensation [1,2], point diffraction [3], and stitching [4], are not universally applicable and have limitations even in their most suited applications. As a consequence, mechanically based measurements by stylus type coordinate measurement machines are used today in all but the most demanding applications even though they do not fulfill all demands. Besides high cost, their main drawbacks are long TACT, poor spatial resolution, and their potential to damage the test part. They are not suited for measurements in the production area.

We present here a new scanning method based on Fizeau interferometry with a spherical reference surface [5]. It has the potential to fulfill the requirements stated before in a very satisfactory way: (1) it can be used for lenses of different sizes and numerical apertures (besides very low NA), (2) covers a large range of aspheric departures, (3) has high spatial resolution, very good TACT time, and (4) does not need tooling (like computer generated holograms or refractive null compensators) and little time for pre-measurement preparations. For lithographic applications, it has proven to provide a very nice combination of small uncertainty and high spatial resolution even for aspheric surfaces with extreme diameters and very large aspheric departure. And last but not least: because it is based solely on distance measurements without a physical reference for the aspheric surface to be tested, it is another of the rare examples in interferometry which falls into the category of "absolute tests".

2. The new method

We restricted ourselves to the measurement of rotationally symmetrical aspheric surfaces. Even though this is still a 3-dimensional problem in the "real world", we can nicely simplify it for the purpose of this paper by considering only the plane through the symmetry axis of the asphere. We understand the problem described with Cylinder Coordinates: h=lateral coordinate, z=axial coordinate and theta=azimuthal angle, and we take theta as being constant.

It is an interesting fact that, for an "ideal" rotationally symmetrical asphere, every point is a "constant" with respect to the variable theta. As a consequence, even though very important, it is not very difficult to measure the "rotationally variant part" (RV-part) of an aspheric surface with very high accuracy by rotating the surface in front of the measurement device [6]. As the measurement value does not change significantly, the "dynamic range" of the problem is low! The opposite is true for the rotationally invariant part (RI-part), which contains the complete description of the aspheric profile to be compared with the aspheric equation given by the quantities c, k and a_i of the equation:

$$z(h)=\left(\frac{c}{1+\sqrt{1-(1+k)c^2h^2}}+a_2\right)h^2+a_3h^3+a_4h^4+...+a_nh^n \qquad (1)$$

$k=$ conic constant, $\quad c=\frac{1}{R_0}\quad$ with $\quad R_0=\frac{\sqrt{\left(1+z'(0)^2\right)^3}}{z''(0)}\quad$ radius of the apex-sphere

$$z'(h)=\frac{c\cdot h}{\sqrt{1-(1+k)c^2h^2}}+2a_2h+3a_3h^2+4a_4h^3+...+n\cdot a_nh^{n-1} \qquad (2)$$

This aspheric profile is the real challenge to be measured with low uncertainty and with high spatial resolution, since z changes rapidly with h, but we show that this problem is "mastered" in an elegant way. This having been said, we now deal with the two-dimensional problem. Fig. 1 shows the important quantities to be investigated:

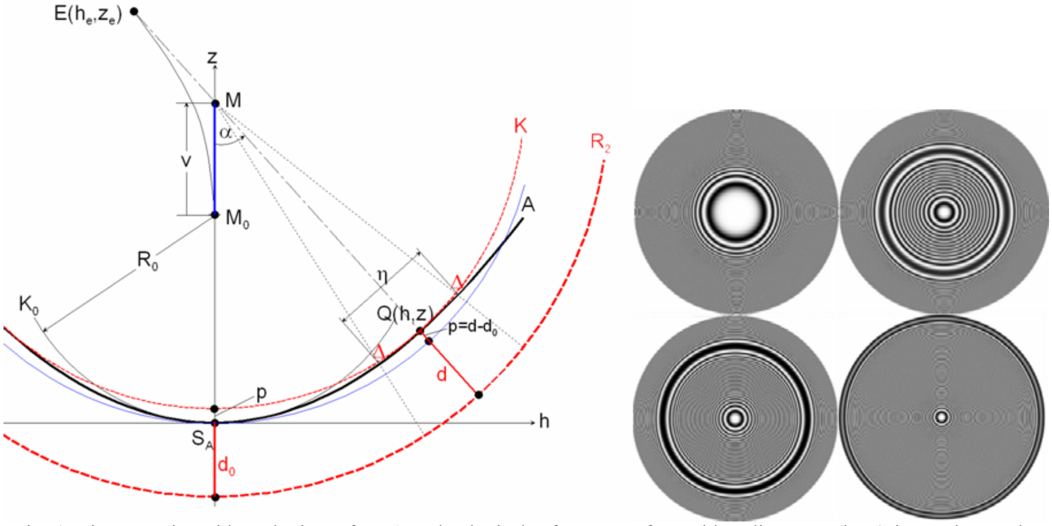

Fig. 1. Fizeau cavity with aspheric surface A and spherical reference surface with radius R_2. $E(h_e,z_e)$ is a point on the "evolute" of the aspheric surface at point Q(h,z). When the surface is scanned (see text), Q(h,z) moves along the aspheric surface, always being located where the rays from the center of the reference sphere M strike the aspheric surface. At the same ray, $E(h_e,z_e)$ is located, moving along the curved line between M_0 and E. The point $E(h_e,z_e)$ is the center of the locally best fitting sphere to point Q(h,z), which has a different radius of curvature R_e than the sphere K, which has the radius $R=R_0+v-p$. Due to the difference of R_e and R, there is a certain "vicinity" η around Q(h,z) where fringes can be resolved by a CCD detector, see the right side of Fig. 1.

In our method [6], the aspheric surface under test is scanned along its symmetry axis and compared against a calibrated, spherical reference surface, i.e., it is a Fizeau arrangement where the thickness of the cavity is changed. At the same time, we measure the distances d_0 at the **apex** and d at the **zone** (same interferogram for both). Starting from the "home position" v=0, i.e. $d_0=R_2-R_0$, we scan the aspheric surface by increasing v (i.e. decreasing d_0). At the same time, the location of the point Q(h,z), starting from $S_A(0,0)$, moves along the aspheric surface and d decreases similarly to d_0, but not totally identical. The difference between d and d_0 is p, which is a measure of the aspheric departure of the surface from a sphere. By simultaneously measuring d_0 and d, we derive the two other quantities $v=d_0-d_{0home}$ and $p=d-d_0$. We now will show mathematically how we can reconstruct (h,z) from (v,p).

The equation for the circle with center point M and radius R on which the point Q(h,z) of the aspheric surface is also located is given by:

$$\left(R_0+v-p\right)^2=h^2+\left(R_0+v-z\right)^2 \qquad (3)$$

When the center point M(v) of the circle K is shifted by an infinitesimal distance *dv*, the radius of the circle grows by another infinitesimal quantity *dp* and the new circle cuts the old circle in the common point Q(h,z) because the aspheric surface A can be seen as the envelope of all circles K. The equation for the new circle is:

$$\left(R_0+(v+dv)-(p+dp)\right)^2=h^2+\left(R_0+(v+dv)-z\right)^2 \qquad (4)$$

As the aspheric surface and the sphere K have a common tangent in Q, the slope of the aspheric surface in Q is z'=tanα and from the Fig. 1 we can see:

$$h=\left(R_0+v-z\right)\cdot\tan\alpha=\left(R_0+v-z\right)\cdot z' \qquad (5)$$

Neglecting squares of infinitesimal small terms, we derive from (3) to (5) the basic equations of our new method:

$$v = z - R_0 + \frac{h}{z'} \qquad (6a)$$

$$h = (R_0 + v - p)\sqrt{p'(2-p')} \qquad (6b)$$

$$p = z + \frac{1-\sqrt{1+z'^2}}{z'} \cdot h \qquad (7a)$$

$$z = p + (R_0 + v - p) \cdot p' \qquad (7b)$$

$$\frac{dp}{dv} = p' = 1 - \frac{1}{\sqrt{1+z'^2}} \qquad (8a)$$

$$\frac{dz}{dh} = z' = \frac{\sqrt{p'(2-p')}}{1-p'} \qquad (8b)$$

We see that 3 quantities, h, z and dz/dh are needed to calculate p and v, given the aspheric equation and its derivative, and also 3 quantities v, p and dp/dv must be measured to derive h and z of the actual surface. We measure p_m and v_m and we compute h_m and z_m; the index m stands for "measurement".

For dp/dv we shift the point M(v) by a small amount to M(v+Δv) and measure the resulting increase Δp of p. Notice the definition for p, which is $p=d-d_0$ as shown in Fig. 1. The difference quotient Δp/Δv is a good approximation of the differential quotient dp/dv and with the different directions of d and d_0 it becomes clear that

$$dp/dv = p' = 1-\cos\alpha \qquad (9).$$

Notice the fact that the line from $M(0,R_0+v)$ to Q(h,z) is normal to the surface, which has the "slope" dz/dh = z' = tanα. Therefore, we have the choice to compute α either according to (9) or equivalently from (8b). When we use α instead of p' = dp/dv as the third variable, then we can rewrite the equations (6b) and (7b) in a more intuitive (see Fig. 1) manner as:

$$h_m = (R_0 + v_m - p_m)\sin\alpha_m = (R_0 + v_m)\cdot\sin\alpha_m - p_m \cdot \sin\alpha_m \qquad (10)$$

$$z_m = (R_0 + v_m) - (R_0 + v_m - p_m)\cos\alpha_m = (R_0 + v_m)\cdot(1-\cos\alpha_m) + p_m \cdot \cos\alpha_m \qquad (11)$$

$$\alpha_m = \arctan\left(\sqrt{p_m'(2-p_m')}, (1-p_m')\right) \qquad (12)$$

3. The aspheric surface near the apex

The accuracy with which the zone in the measured phase-map can be located depends on the derivative dp/dh. When the center $E(h_e,z_e)$ of the evolute is close to M, or more precise, if $|R/R_e| \approx 1$, where R_e and R are the distances from Q to M, Q to E, then dp/dh becomes small. For instance, this is the case near the vertex, where the aspheric surface is close to a sphere. In such cases, the zone is very "broad" and the value for p changes only very slowly with α. Then there is no harm in measuring with one value for v_m several different values of p_m at different locations in the phase-map. The associated values for α_m in (10) and (11) can still be found experimentally by shifting v to v+Δv and measuring p+Δp, and using Eq. (9).

4. Why is the new method superior?

The new scanning method based on Fizeau interferometry provides benefits for the user, as it is applicable to steep as well as mild aspheric surfaces, has very good TACT time and needs no tooling like CGH or null-compensation lenses. And, the expert in interferometry will also notice that it is superior by principles generally valid in metrology:

(1) It is solely based on *interferometric distance measurements,* (2) It measures only *relative* distances between two *solid bodies*, the aspheric lens surface and the spherical reference surface, (3) It always automatically measures where the *optical conditions are optimal,* at the zones of *normal* incidence, (4) The "dynamic range" of the problem is *minimized through scanning,* (5) The lateral coordinate is derived from the phase measurement, (6) The magnification or distortion of the imaging optics of the interferometer do *not influence* the result, (7) There are *no additional parts* that must be introduced and *aligned,* (8) It is very obvious what is measured, so it is a "*traceable method*", (9) It does *not* rely on *secondary* standards and (10) Every measured zone is *independent* from all others; *no* stitching with its inherent errors is used.

5. References

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