Precision Glass Molded Lenses Analysis via Null-Screen Test

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Abstract. This work shows a method to recover the shape of the precision glass molding surface via null-screen test. For the validation of the proposed method, we analyzed the ACL25416U condenser lens fabricated by Thorlabs. The results show that the conic constant, the radius of curvature and the aspheric deformation coefficients can be retrieved with good accuracy.

1. Introduction
The aspherical surfaces with polynomial expansion have taken an important role in the areas of optical systems, astronomical instrumentation, illumination, among others [1-4]. Nevertheless, is well known that if the complexity of the surface increase, it leads to having greater challenges in the optical testing and polishing areas. Is for this reason that, one of the major challenges is to verify the optical quality of each surface. In recent years, the incursion of CNC machines has revolutionized the optical manufacturing field [5], this since with these machines it is possible to manufacture, in a simple way, aspherical surfaces with polynomial expansion.

For this purpose, we decided to use the technique of null-screens [6]. This technique allows us to evaluate specular or partially reflective surfaces without contact, it is very robust and easy to handle, and besides of that, this method can analyze very large surfaces with a wide range of shapes [7].

2. Null-screen method
The basic configuration of the null-screen test (figure 1) consists of drawing a set of curved lines or nearly elliptical spots on a cylinder, a plane, or a cone in such way that by reflection on the test surface, the image consists of a perfect square grid or an array of circular spots [8]. if the surface is ideal or has a low irregularity, the image observed, is a perfect array of lines or dots [6-9]. However, if the surface is not the ideal, or is not the surface for which the null-screen was designed, the observed image shows departures from a perfect array. The differences between the perfect array (theoretical) and the deformed array (experimental), give us relevant information about the shape of the surface that is being analyzed [10-12].
From equation of the sagitta which describes this type of surface given by

\[ f(x_3,y_3,z_3) = Q(z_3 - z_0)^2 - 2r(z_3 - z_0) + s^2 + P^2 Q - 2PQ(z_3 - z_0) + 2rP , \]  

(1)

were \( x_0, y_0 \) and \( z_0 \) are the surface decentering, \( s^2 = (x_3 - x_0)^2 + (y_3 - y_0)^2 \), \( Q \) is defined like the conic constant minus one \((k+1)\), and \( P \) can take the form of any polynomial function.

To obtain the coordinates where the reflected ray intersects the cylinder, we start from the equation of the cylinder with radius \( C \)

\[ (x_0' - x_0)^2 - (y_0' - y_0)^2 = C^2 . \]  

(2)

The parametric equations of the reflected ray are defined by

\[ x_4 = x_1 + R_x \lambda, \]
\[ y_4 = y_1 + R_y \lambda, \]
\[ z_4 = z_1 + R_z \lambda + z_0', \]  

(3)

where \( x_0', y_0' \) and \( z_0' \) are the cylinder decentering, while \( R_x, R_y \) and \( R_z \) are defined as

\[ R_x = -x_1 + 2D_x[F] \left[ \frac{x_1D_x[F] + y_1D_y[F] + aD_z[F]}{(D_x[F])^2 + (D_y[F])^2 + (D_z[F])^2} \right]_{i}, \]
\[ R_y = -y_1 + 2D_y[F] \left[ \frac{x_1D_x[F] + y_1D_y[F] + aD_z[F]}{(D_x[F])^2 + (D_y[F])^2 + (D_z[F])^2} \right]_{i}, \]
\[ R_z = -z_1 + 2D_z[F] \left[ \frac{x_1D_x[F] + y_1D_y[F] + aD_z[F]}{(D_x[F])^2 + (D_y[F])^2 + (D_z[F])^2} \right]_{i}. \]  

(4)

Substituting the equation (3) into (2), matching up \( \lambda \) terms we have

\[ O\lambda^2 + L\lambda + T = 0 . \]  

(5)

Where

\[ O = R_x^2 + R_y^2, \]
\[ L = 2x_3R_x - 2x_0R_x + 2y_3R_y - 2y_0R_y, \]
\[ T = x_3^2 + x_0^2 - 2x_3x_0 + y_3^2 + y_0^2 - 2y_3y_0 + C^2. \]  

(6)

Solving with the quadratic formula for \( \lambda \)

\[ \lambda = \frac{-L \pm \sqrt{L^2 - 4OT}}{2O}. \]  

(7)

With this, we obtain the coordinates \( x_4, y_4, \) and \( z_4 \), which correspond to the positions where the rays reflected by the surface intersect the display.
3. Real surface analysis

In this section is shown the quantitative analysis of the ACL25416 condenser lens aspherical surface. The analysis was carried out using a ReRRCA algorithm variant, which we described in [8], and the mathematical basis described in [9]. This algorithm is an alternative method to recover the shape of the surface through randomized algorithms (figure 2). In this case, instead of a direct integration process as is commonly performed, the shape of the surface is recovered in a direct way. With this method, the integration errors are avoided so the total error is dramatically reduced because most of the errors are added up during the reconstruction of the surface by the integration process [8].

**Figure 2.** Flowchart of the proposed algorithm.

In figure 3 the calculated null-screen for the analysis of the aspherical surface is shown.

**Figure 3.** Calculated null-screen for the aspherical surface.

In figure 4b) is shown the image captured experimentally, while in figure 4c) is shown its binarization.
In this section is presented the analysis of the aspherical surface of the condenser lens ACL25416U fabricated by Thorlabs (figure 4a). The equation that describes the surface shape is defined as

$$z = \frac{S^2}{r \left[1 + \sqrt{1 - (1+k) \frac{S^2}{r^2}}\right]} + A_1 S^4 + A_2 S^6 + A_3 S^8 + A_4 S^{10}$$  \hspace{1cm} (8)$$

where $S = (x^2 + y^2)^{1/2}$, $r$ is the radius of curvature and $A_1, A_2, A_3, A_4$ are the deformation coefficients.

In Table 1 is shown a comparison between the design coefficients (theoretical coefficients) against the coefficients recovered by our algorithm.

|        | Design value | Recovered value | Difference |
|--------|--------------|-----------------|------------|
| $r \ (mm)$ | 8.8181       | 8.5703          | 0.2479     |
| $k$    | -0.9992      | -0.9936         | 0.0055     |
| $A_1$  | 8.682167e-05 | 7.875514e-05   | 8.0665E-06 |
| $A_2$  | 6.376012e-08 | 5.747310e-08   | 6.287E-09  |
| $A_3$  | 2.407308e-09 | 2.355055e-09   | 5.225E-11  |
| $A_4$  | -1.718902e-11| -2.330184e-11  | 6.1128E-12 |
| $x_0 \ (mm)$ | 0.0          | 0.09725383     | 0.09725383 |
| $y_0 \ (mm)$ | 0.0          | -0.11633844    | -0.11633844|
| $z_0 \ (mm)$ | 0.0          | -0.44217811    | -0.44217811|
| $x_0' \ (mm)$ | 0.0          | 0.06916008     | 0.06916008 |
| $y_0' \ (mm)$ | 0.0          | -0.09249101    | -0.09249101|
| $z_0' \ (mm)$ | 0.0          | 0.07574529     | 0.07574529 |

The effective focal length recovered by our program was 15.49456 mm, a difference of 0.50544 mm corresponding to 3.159%. This difference in EFL is within specifications of the fabricant that it is ±8%.
4. Conclusions
In this work, we have proposed a new method to evaluate a precision glass molding lens with the null-screen test variant of the ReRRCA algorithm. The accuracy of the presented method to recover the radius of curvature and the conic constant was around 3% and 0.6%, respectively. In the case of the aspheric deformation coefficients the average error was around 14%. It is important to note that these values were obtained by comparing our results against the design values, so these errors can be reduced if we compare our results against other analysis methods. Finally, with this method we can extract the parameters of interest by a simple procedure and to make a direct analysis of the fast aspherical surface with polynomial expansion, avoiding polynomial fits to the recovered shape, and reducing the errors, this issue is critical for the design and fabrication of such surfaces.

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