3D measurement and characterization of ultra-precision aspheric surfaces

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Abstract

National Metrology Institutes (NMIs), engineering schools and industries have started to conduct research in the area of aspherical optics. Aspheres are replacing traditional spherical optics since they eliminate spherical aberrations, and by that, have become widely used in various fields such as imaging, photonics, and ophthalmology. The roughness of aspherical surfaces is usually restrained to $\lambda/20$, nonetheless the form error is more complicated to control and is hardly below few hundred nanometres. In metrology, roughness and form characterizations also represent a real challenge especially when considering a large number of data points. This paper presents a comparison, based on form defects evaluation, between measurements of an aspherical lens performed by tactile and optical single scanning probes. Both probes are integrated on the LNE ultra-high precision profilometer traceable to the meter definition (SI). Data processing presents a challenge for aspherical form characterization. Currently no software is available in the market to perform such analysis. Though, a non-linear Orthogonal Least-Squares optimization method based on the Levenberg-Marquardt is developed to fit the theoretical model of the aspherical lens to the measured data.

1. LNE high precision profilometer

LNE's high precision profilometer is a measurement machine (Fig.1) capable of performing independent motions in all x, y and z directions using three independent high-precision mechanical guiding systems equipped with encoders. While x and y motions are controlled by sub-nanometer resolution laser interferometers, the z motion is controlled by a differential laser interferometer that allows to shorten the metrology loop and maintain a sub-nanometric accuracy.

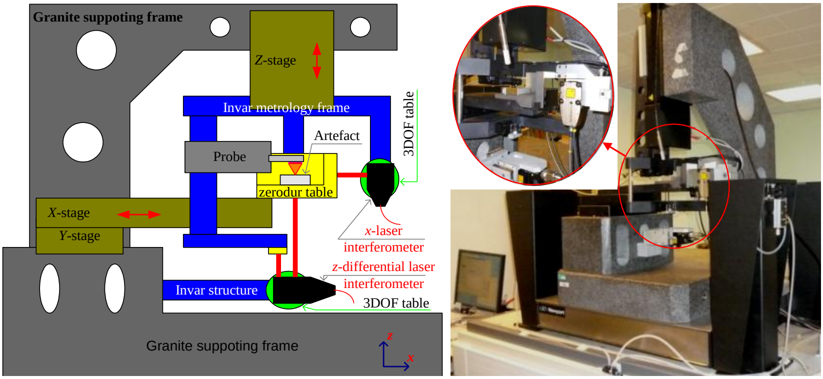

Fig.1: Design and photo of the LNE's high precision profilometer

The working range in the xy-plane is 50×50 mm². The probe and its supporting structure are mounted on the vertical guiding system along which the measurement is done. The working range of the mechanical guiding system in z-direction is about 100 mm. The supporting frame is made of massive granite and carries the guiding elements. The metrology frame is made of Invar for minimal sensitivity to environmental influence.

The metrology loop incorporates three Renishaw laser interferometers and is equipped either with a chromatic confocal probe or a tactile probe to achieve nanometric resolution. The machine allows the in-situ calibration of the probes by means of a differential laser interferometer considered as a reference.

The uncertainty budget is established for the measurement of KNT4080-30 V-groove standards taking into consideration different and various error sources with the addition of the measuring probe's errors. The obtained results validate the capability of the profilometer to perform measurement at the nanometer level of accuracy.

2. Optical and tactile scanning of aspherical surfaces

The tactile and optical measurements of the asphere take place in the LNE's cleanroom in which environmental conditions are optimal. Temperature is controlled to 20±0.3 °C and humidity to 50±5 %RH. The asphere is posed on the Zerodur table

(Fig.1) and is measured by a tactile single point scanning probe which has been previously calibrated in-situ. Since it is not possible to exactly align the asphere's axis with the z axis of the measurement, an approximation of the apex position can be done by estimating the cusp of the surface. For this matter, the surface is scanned once in the x- direction and once in the y- direction and a peak is computed. A large number of data points (~ 1,500,000 points) are recorded in the form of XY-grids (ranging from 5×5 mm² to 6×6 mm²). The optical probe's total measurement time is about half of the tactile probe's total measurement time since no contact needs to be established for the optical measurement. The traditional way to represent aspherical surfaces is the axially symmetric quadric and power series parametric description as described in ISO 10110-Part 12.

$$z = \frac{cr^2}{1+\sqrt{1-(1+\kappa)\,c^2r^2}} + \sum_{j=2}^{m} A_{2j} r^{2j}, \tag{1}$$

Where r is the radial coordinate, z is the sag (sagittal representation), c is the curvature at the apex, and κ is the conic constant. The $A_{2j}r^{2j}$ terms are the higher order aspheric terms that represent the additive departure from the quadric.

3. Aspherical surface fitting

The form evaluation of aspheres can be done by fitting the measured data onto the aspherical model according to a criterion such as least-squares or minimum zone. The residual errors of the deviations to the associated reference model are evaluated. The Peak-to-Valley (PV) and the Root-Mean-Square (RMS) are the most widely adopted parameters for the assessment of form deviations of aspherical surfaces, roughness being independent of form errors. Chen *et al* [1] propose an aspherical lens characterization by means of a 2D profile fitting. The dataset used is a profile measured using a stylus probe and the reference model is the corresponding asphere profile. The fitting is done using the Levenberg-Marquardt algorithm [2] for its quick convergence and precision. This method has been recommended by the NIST.

$$\min_{\xi} \sum_{i=1}^{N} \left\| \mathrm{R}p_i + \mathrm{T} - q_i \right\|^2, \tag{2}$$

ξ is the set of shape, position and orientation variables, **R**, **T** are transformation parameters, p_i is the data point, and q_i is the orthogonal projection of the data point p_i onto the reference model (footpoint). In this paper, position and orientation parameters as well as shape parameters are estimated. The process described here goes by optimizing for five transformation parameters, the symmetry about z axis is being redundant here. The objective function to minimize is then given by the following equation

$$\min_{c,\kappa,\alpha;\theta,\gamma,t_x,t_y,t_z} \sum_{i=1}^{N} \left\| \mathrm{R}_{\theta,\gamma} p_i + \mathrm{T} - q_i \right\|^2, \tag{3}$$

The fitting method is used to fit and analyze the recorded tactile and optical data and the results are illustrated in Fig.2. The RMS and PV of the residual errors are of 217 nm and 2198 nm for the tactile measurement and 336.40 and 6160.73 for the optical measurement.

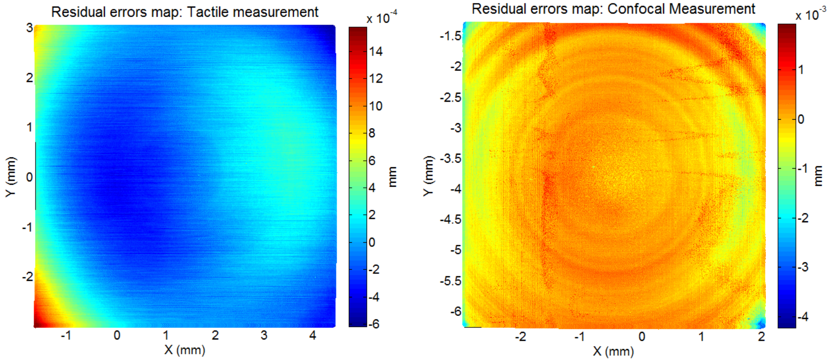

Fig.2: Residual error maps. Left: tactile measurement, right: optical measurement.

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