Non-contact Measurement Machine for Freeform Optics

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The performance of high-precision optical systems using spherical optics is limited by aberrations. By applying aspherical and freeform optics, the geometrical aberrations can be reduced or eliminated while at the same time also reducing the required number of components, the size and the weight of the system. New manufacturing techniques enable creation of high-precision freeform surfaces. Suitable metrology (high accuracy, universal, non-contact, large measurement volume and short measurement time) is key in the manufacturing and application of these surfaces, but not yet available. In this thesis, the design, realization and testing of a new metrology instrument is described. This measurement machine is capable of universal, non-contact and fast measurement of freeform optics up to Ø500 mm, with an uncertainty of 30 nm (2\sigma).

A cylindrical scanning setup with an optical distance probe has been designed. This concept is non-contact, universal and fast. With a probe with 5 mm range, circular tracks on freeform surfaces can be measured rapidly with minimal dynamics. By applying a metrology frame relative to which the position of the probe and the product are measured, most stage errors are eliminated from the metrology loop. Because the probe is oriented perpendicular to the aspherical best-fit of the surface, the sensitivity to tangential errors is reduced. This allows for the metrology system to be 2D. The machine design can be split into three parts: the motion system, the metrology system and: the non-contact probe.

The motion system positions the probe relative to the product in 4 degrees of freedom. The product is mounted on an air bearing spindle (0), and the probe is positioned over it in radial (r), vertical (z) and inclination (ψ) direction by the R-stage, Z-stage and Ψ-axis, respectively. The motion system provides a sub-micrometer repeatable plane of motion to the probe. The Z-stage is hereto aligned to a vertical plane of the granite base using three air bearings, to obtain a parallel bearing stage configuration. To minimize distortions and hysteresis, the stages have separate position and preload frames. Direct drive motors and high resolution optical scales and encoders are used for positioning. Mechanical brakes are applied while measuring a track, to minimize power dissipation and to exclude encoder, amplifier and EMC noise. The motors, brakes and weight compensation are aligned to the centres of gravity of the R and Z-stage. Stabilizing controllers have been designed based on frequency response measurements.

The metrology system measures the position of the probe relative to the product in the six critical directions in the plane of motion of the probe (the measurement plane). By focussing a vertical and horizontal interferometer onto the Ψ-axis rotor, the displacement of the probe is measured relative to the reference mirrors on the upper metrology frame. Due to the reduced sensitivity in tangential direction at the probe tip, the Abbe criterion is still satisfied. Silicon Carbide is the material of choice for the upper metrology frame, due to its excellent thermal and mechanical properties. Mechanical and thermal analysis of this frame shows nanometer-level stabilities under
the expected thermal loads. Simulations of the multi-probe method show capabilities of in process separation of the spindle reference edge profile and the spindle error motion with sub-nanometer uncertainty.

The non-contact probe measures the distance between the Ψ-axis rotor and the surface under test. A dual stage design is applied, which has 5 mm range, nanometer resolution and 5° unidirectional acceptance angle. This enables the R and Z-stage and Ψ-axis to be stationary during the measurement of a circular track on a freeform surface. The design consists of a compact integration of the differential confocal method with an interferometer. The focusing objective is positioned by a flexure guidance with a voice coil actuator. A motion controller finds the surface and keeps the objective focused onto it with some tens of nanometers servo error.

The electronics and software are designed to safely operate the 5 axes of the machine and to acquire the signals of all measurement channels. The electronics cabinet contains a real-time processor with many in and outputs, control units for all 5 axes, a safety control unit, a probe laser unit and an interferometry interface. The software consists of three main elements: the trajectory planning, the machine control and the data processing. Emphasis has been on the machine control, in order to safely validate the machine performance and perform basic data-processing.

The performance of the machine assembly has been tested by stability, single track and full surface measurements. The measurements focus on repeatability, since this is a key condition before achieving low measurement uncertainty by calibration. The measurements are performed on a Ø100 mm optical flat, which was calibrated by NMi VSL to be flat within 7 nm rms. At standstill, the noise level of the metrology loop is 0.9 nm rms over 0.1 s. When measuring a single track at 1 rev/s, 10 revolutions overlap within 10 nm PV. The repeatability of three measurements of the flat, tilted by 13 µm, is 2 nm rms. The flatness measured by the uncalibrated machine matches the NMi data well. Ten measurements of the flat tilted by 1.6 mm repeat to 3.4 nm rms.

A new non-contact measurement machine prototype for freeform optics has been developed. The characteristics desired for a high-end, single piece, freeform optics production environment (high accuracy, universal, non-contact, large measurement volume and short measurement time) have been incorporated into one instrument. The validation measurement results exceed the expectations, especially since they are basically raw data. Future calibrations and development of control and data-processing software will certainly further improve these results.