Abstract

Freeform surfaces are emerging in a new design trend in the optical industry to improve the system performance with reduced number of optical components. These surfaces are featured with non-symmetrical profile and offer added advantages over rotationally symmetric surfaces while designing a compact and light weight optical system. Freeform surfaces found their usage mostly in non-imaging and imaging applications such as a compact projection system, head-up displays, lithography, computational imaging, space optics, and optical microsystems. Present optical design trend and advancement of precision manufacturing technology is driving the researchers for usage of freeform surfaces in imaging application i.e. space optics and high depth of focus thermal imaging systems. Along with the advantages, there are numerous challenges in the fabrication and characterization of such complex surfaces.

Modern optical fabrication methods are, in principle, capable to meet the challenges to generate the complicated freeform shapes. However, the metrology is still challenging and a limiting factor for achieving precision fabrication tolerances on the freeform surfaces. To achieve precision fabrication tolerances using high end computer numerically controlled (CNC) machines, a suitable metrology system is required to provide feedback to minimize the residual form error of designed freeform surface. Existing profilometry and interferometry based metrology techniques have their own challenges and limitations for measurement of freeform surface.

The wavefront measurement capability of the Shack-Hartmann Sensor (SHS) has brought its applications in the measurement of freeform surfaces with the advantage of being compact, low cost, vibration insensitive and non-null in nature as compared to null based interferometric approaches. This also makes SHS a suitable candidate for on-machine freeform metrology solution to provide metrology feedback for corrective machining of freeform optics. SHS is a low resolution sensor and dynamic range of the measurement is limited by the slope of the surface under test. These limitations can be addressed using specific subaperture stitching techniques and scanning SHS configuration for profiling freeform optics/wavefront. The goal of the research work is to develop a subaperture stitching algorithm and its implementation to Shack-Hartmann Sensor based metrology methodology for the measurement of freeform surfaces.

The following major investigations have been carried out to achieve the goal of the research work in the thesis

- Subaperture stitching interferometry (SSI) based techniques have been studied and implemented for the measurement of optical surfaces including plano, aspherical and cubic surface.
- A subaperture stitching algorithm and stitching tool box compatible with design, manufacturing and testing platform has been developed and implemented for freeform metrology using scanning SHS configuration.
- An improved reconstruction algorithm has been developed for noisy slope data of freeform surface using weighted cubic spline based integration (WCSLI) and implemented to scanning SHS based freeform metrology with improved stitching performance.
- A precise registration based subaperture stitching technique has been investigated using an iterative closest point (ICP) based approach and an intrinsic surface feature (ISF) based approach for addressing the alignment issues during subaperture stitching process.

The first chapter presents a general overview of freeform optics. Advantages of freeform optics for use in non-imaging and imaging applications are highlighted. The challenges in the designing of freeform optics with basic mathematical background and performance evaluation are discussed. The trends in the manufacturing of freeform surfaces are studied and their limitations for achieving precision manufacturing tolerances are discussed. In the last section, a survey has been made on various metrology techniques explored for characterization of freeform surfaces with their limitations.

In the second chapter, basic principle of SSI for testing of optical wavefront is discussed. SSI based techniques are implemented for the measurement of flat and aspheric surfaces by stitching circular and annular subapertures to compute phase profile of full surface. The technique has also been implemented for the measurement of shallow cubic freeform surface during its corrective CNC polishing process. Finally, the limitations of subaperture stitching interferometry for the measurement of freeform surfaces have been discussed.

In the third chapter, a slope based measurement of freeform wavefront using scanning SHS has been demonstrated. A method based on subaperture stitching for measurement of freeform wavefront is developed and applied to the data acquired using a scanning SHS. A mathematical model for a stitching algorithm is developed. The simulation results based on mathematical model is experimentally verified on the freeform surfaces. The proposed method is an effective approach, for freeform metrology in non-imaging applications. By increasing the accuracy of the misalignment correction during the stitching, it can be applied measurement of freeform optics for imaging applications.

The fourth chapter presents spline based integration technique for the reconstruction of a freeform wavefront from slope data. The slope data of freeform surface contains noise due to its machining process and introduces reconstruction error. WCSLI has been developed for integration of noisy slope data to reconstruct the freeform surface profile. The technique has been experimentally implemented to subaperture stitching based measurement of a freeform wavefront using a scanning Shack-Hartmann sensor. The boundary artifacts are minimal in WCSLI based reconstruction and provide improved performance of subaperture stitching process for measurement taken by using SHS noisy freeform surfaces due to machining tool marks.

In the fifth chapter, registration based lateral misalignment correction scheme for subaperture stitching process is presented. In the first section of the chapter, an ICP based registration scheme is proposed to minimize lateral misalignments induced during scanning process. ICP perform well for correction of misalignment of the order of integer value of sample size of measurement taken by SHS. In the next section, a precise registration scheme based on ISF with up-sampled cross correlation is presented which demonstrated the better misalignment correction for sub-sampled order lateral misalignments and thus enhanced the performance of stitching process.

The sixth chapter presents the conclusions drawn from the research work, advantages and limitation of scanning SHS based freeform metrology and future scope of the research work.