SCANNING SHACK-HARTMANN WAVEFRONT SENSOR BASED MEASUREMENT SCHEME FOR ASPHERIC AND FREEFORM OPTICS

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“The LORD has made everything for his own purposes” - Proverbs 16:4

Dedicate to

Almighty GOD

“This world is fading away, along with everything it craves. But if you do the will of God, you will live forever”

- 1 John 2:17

Certificate

This is to certify that the thesis entitled "**SCANNING SHACK-HARTMANN WAVEFRONT SENSOR BASED MEASUREMENT SCHEME FOR ASPHERIC AND FREEFORM OPTICS**" submitted by **DALI RAMU BURADA** to the Instrument Design Development Centre, Indian Institute of Technology Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY**. This thesis is a bonafide record of the research carried out by him under my guidance and supervision. In my opinion the thesis has reached the standards fulfilling the requirements for the submission relating to the degree.

The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Date:

Place:

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Associate Professor

Instrument Design Development Centre

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"Do not conform yourselves to the standards of this world, but let God transform you inwardly by a complete change of your mind. Then you will be able to know the will of God" - Romans 12:2

Abstract

This thesis is the result of the research work has been carried out at Instrument Design Development Centre (IDDC), Indian Institute of Technology (IIT) Delhi, India and Department of Technical Optics, Technical University (TU) Ilmenau, Germany through Indo-German DST-DAAD Project Based Personnel Exchange Programme 2013-2015.

The goal of the research work is the development of a scanning Shack-Hartmann sensor (SHS) based measurement scheme for aspheric and freeform optics. The freeform optical surfaces are increasingly becoming integral part of optical systems as they offer higher degrees of freedom to the designer in order to improve the performance. Particularly benefited systems are illumination systems, compact projection systems, head-up-displays, ophthalmic systems, and surveillance systems.

The increased range of manufacturable freeform surfaces offered by the new fabrication techniques is giving opportunities to incorporate them in the optical systems. However, the success of these fabrication techniques depends on the capabilities of metrology procedures and a feedback mechanism for optimizing the manufacturing process. Therefore, a precise and *in-situ* metrology technique for the measurement of freeform optics is in demand. Though all the techniques available for aspheres have been extended for the freeform surfaces by the researchers, but none of the techniques has yet been incorporated into the manufacturing machine for *in-situ* measurement. The most obvious reason is the complexities involved in the optical setups to be integrated in the manufacturing platforms. The SHS offers the potential to be incorporated into the machine environment due to its less vibration sensitivity, compactness and 3D shape measurement capability from slope data. However, the measurements are limited by the lateral resolution offered by the SHS. The SHS has the potential to be integrated on to the machine environment for *in-situ* measurement process.

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

- A scanning Shack-Hartmann sensor based metrology technique (non-null configuration) with subaperture stitching scheme has been developed for measurement of freeform optics in both in transmission mode and reflection mode.

- Measurement of freeform optics using diffractive null element which can compensate the departure of the freeform surface under test from flat.
- Further, metrology technique for freeform optics in reflection mode is developed and the metrology scheme has been enhanced that it can be suitable for *in-situ* measurement and corrective machining of freeform optics.

An in-house subaperture stitching algorithm has been developed for freeform wavefront at IIT Delhi. The first experimental investigations are carried at TU Ilmenau, Germany for the validation of the subaperture stitching algorithm using a scanning SHS. Further, a detailed experimental investigations on the measurement of freeform optics have been performed in both transmission and reflection mode at IIT Delhi, India. Both the simulations and experimental investigations are also conducted in detail to know the influence of various parameters such as the alignment of the freeform, slope, stitching sequence and other stitching parameters on to the final surface profile error.

The second investigation on the measurement of freeform optics by using a Mach-Zehnder interferometric configuration based on Diffractive Optical Element has been developed at TU Ilmenau, Germany. The setup is developed in a switchable mode where both the SHS and CCD are used as measurement heads. Experiments are conducted in this configuration and the results are presented.

Finally, measurement of freeform optics in reflection mode is conducted to know only fabrication error on the surface profile and further, the metrology scheme has been enhanced as that can be a suitable for *in-situ* measurement and corrective machining of freeform optics. A quantitative analysis on positioning errors, overlapping between the adjacent subapertures overlapping area and position for the measurement scheme has also been performed.

It is expected that the results of this study will substantially increase the accuracy of the production and testing of high-performance aspheric optics.

The first chapter presents the overview of the freeform optics in various imaging and non-imaging applications, advantages over conventional/rotationally symmetric optics, challenges involved in the design, fabrication, metrology and integrations of freeform optics in the optical systems. Further, it focuses on the current status and the development of the ongoing research on the freeform metrology technique. The second chapter discusses the details on Shack-Hartmann sensor (SHS) such as the principle of operation, design parameters and wavefront reconstruction algorithms. Further, the application of a scanning SHS for the measurement of freeform optical surfaces and mathematical modelling with experimental validation for subaperture stitching of freeform wavefront are also presented.

In third chapter, a detailed investigations on the development of metrology technique for freeform optics using a non-interferometric method like a scanning SHS are discussed. It mainly focuses on the alignment library for the freeform optics, subaperture stitching sequences, experimental investigations on both freeform and aspheres. A detailed analysis of the effects of slope and positioning error on the reproducibility is presented. The fourth chapter describes the development of DOE Mach-Zehnder interferometric configuration (MZI) for freeform optics. Further, measurement of asphere by using a Zygo Verifire Asphere is presented for the validation purpose.

In the fifth chapter, development of a metrology technique for freeform optics using SHS in reflection mode. The sixth chapter describes the development of a Shack-Hartmann sensor based metrology technique that can be used for quantitative *in-situ* measurement of freeform optics. Measurement procedure using a scanning SHS followed by CNC tool path for freeforms in off-line mode is presented. Repeatability and reproducibility tests of the measurement scheme have also been presented. In the seventh chapter, the current limitations of the scanning SHS based metrology, its advantages and the scope for future studies are discussed as conclusions.

सार

प्रस्तुत शोध, आई डी डी सी, आई आई टी दिल्ली, भारत तथा तकनीकी प्रकाशिकी विभाग , तकनीकी विश्वविद्यालय इल्मेनॉ, जर्मनी के बीच संयुक्त इंडो-जर्मन डीऐसटी - डीएएडी परियोजना हेतु कार्मिक हस्तान्तरण (Personnel Exchange) कार्यक्रम २०१३-१५ के अंतर्गत किये गए अध्ययन का परिणाम है ।

इस शोध कार्य का उद्देश्य एस्फेरिक एवं फ्रीफॉर्म ऑप्टिक्स के परीक्षण हेतु स्कैनिंग शैक-हार्टमैन सेंसर(Scanning Shack-Hartmann sensor) का विकास करना है। फ्रीफॉर्म ऑप्टिक्स का प्रयोग हैई डिग्री ऑफ फ्रीडम होने के कारण ऑप्टिकल सिस्टम की कार्यशक्ति को बढ़ाने हेतु उन्नत अभिकल्प में किया जाने लगा है। विशेषकर इल्लुमिनेशन प्रक्रम कॉम्पैक्ट प्रोजेक्सन सिस्टम, नेत्र सिस्टम और निगरानी प्रक्रमों में प्राय: इनको उपयोग किया जाने लगा है। उन्नत निर्माण विधियों के उपलब्ध होने के कारण फ्रीफॉर्म को प्रकाशीय प्रक्रमों में उपयोग करने का मार्ग प्रशस्त हुआ है। जबकि इनको निर्माण प्रक्रिया को परीक्षण प्रक्रिया निर्धारित करती है क्योंकि निर्माण अनुकूलन हेतु मशीन को इन-सीटू (in-situ) परीक्षण की आवश्यकता होती है जो की अभी उपलब्ध न होने के कारण शोध का विषय है। यद्यपि एस्फेरिक प्रकाशीय सतहों हेतु प्रयुक्त होने वाली विधियों को फ्रीफॉर्म हेतु प्रयोग में लाने हेतु शोध किया जा रहा है। परन्तु कोई भी विधि अभी तक संपूर्ण रूप से विकसित नहीं हुयी है जिसे कि निर्माण प्रक्रिया हेतु मशीन में उपयोग किया जा सके।

शैक-हार्टमैन सेंसर को कम्पन प्रतिरोधी, छोटे आकार, त्रि-आयामी आकार माप किये जाने के कारण मशीन पर लगा पाना संभव है। यद्यपि इसका लेटरल रेसोलुशन कम है परन्तु मशीन पर उपयोग किये जा सकने से इसकी उपयोगिता की जा सकती है।

प्रयुक्त शोध में निम्नलिखित कार्य किये गए -

१) स्कैनिंग तकनीक पर आधारित शैक-हार्टमैन सेंसर का फ्रीफॉर्म प्रकाशीय सतहों पर परावर्तन एवं पारगमित विधियों पर अध्ययन कर युक्ति का विकास किया गया

२) डिफ्रैक्टिव नल प्रकाशीय सतह (Diffractive Null Optical Element (DOE)) का फ्रीफॉर्म के परीक्षण में प्रयोग

३) परावर्तन विधि पर आधारित तकनीक का इन-सीटू परीक्षण का मशीन उपयोगिता तथा करेक्टिव पॉलिशिंग में उपयोग का विकास

सब-अपर्चर स्टिचिंग सॉफ्टवेयर(Subaperture Stitching Software) का विकास आई आई टी दिल्ली, भारत में किया गया। और पहला प्रयोगात्मक परीक्षण तकनीकी विश्वविद्यालय इल्मेनॉ, जर्मनी में किया गया तदुपरांत आई आई टी दिल्ली में परावर्तन एवं परगमि में प्रयोगात्मक कार्य किया गया है। मैक-जेंडर इंटेफेरोमेटेर पर आधारित डी ओ ई प्रयुक्त (DOE) विधि का विकास भी तकनीकी विश्वविद्यालय इल्मेनॉ,एवं आई आई टी के संयुक्त शोध पर किया गया।

परावर्तन विधि से फेब्रिकेशन त्रुटियों का अध्ययन कर करेक्टिव पॉलिशिंग में उपयोग किया गया है। उक्त शोध से यह आशा कि जाती हैं कि एस्फेरिक व् फ्रीफॉर्म सतहों के फेब्रिकेशन कि शुद्धता में वृद्धि होगी परिशुद्ध टेस्टिंग प्रणाली का उपयोग फ्रीफॉर्म व एस्फेरिक सतहों के लिये किया जा सकेगा।

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List of abbreviations

CMM	Coordinate Measurement Machine
DTM	Diamond Turning Machines
DMI	Displace Measuring Interferometer
FTS	Fast Tool Servo
FZI	Fizeau Interferometer
HWP	Half-Wave Plate (or λ/2 Wave Plate)
HSF	High Spatial Frequency
LSF	Low Spatial Frequency
MZI	Mach-Zehnder Interferometric
MRF	Magnetorheological Finishing
MSF	Mid-Spatial Frequency Deviations
NURBS	Non-Uniform Rational Basis Spline
PV	Peak-To-Valley
PGI	Phase Grating Interferometer
PMD	Phase Measuring Deflectometry
PSI	Phase-Shifting Interferometer
PZT	Piezoelectric Transducer
PSF	Point Spread Function
PBS	Polarizing Beam Splitter
PMMA	Polymethyl methacrylate
QWP	Quarter-Wave-Plate(or λ/4 Wave Plate)

RBFS	Radial Basis Functions
RMS	Root-Mean-Square
SHS	Shack-Hartmann Sensor
STS	Slow Tool Servo
SSIA/ASITM	Subaperture Stitching Interferometer for Asphere
SSI	Subaperture Stitching Interferometer
TWI	Tilted Wave Interferometry
TGI	Twyman-Green Interferometry
UA3P	Ultrahigh Accurate 3D Profilometer
UPM	Ultra-Precision Machining