INVESTIGATIONS ON THE SUBAPERTURE STITCHING BASED TECHNIQUES FOR MEASUREMENT OF ASPHERIC AND FREEFORM OPTICS

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OCTOBER 2020

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by

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Submitted

in fulfilment of the requirements for the degree of Doctor of Philosophy

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

OCTOBER 2020

Dedicate to

Almighty GOD

&

My beloved family

"It always seems impossible until it is done"

Certificate

This is to certify that the thesis entitled **"INVESTIGATIONS ON THE SUBAPERTURE STITCHING BASED TECHNIQUES FOR MEASUREMENT OF ASPHERIC AND FREEFORM OPTICS "** submitted by Kamal Kishor Pant to the Centre for Sensors, Instrumentation and Cyber-physical Systems Engineering (SeNSE), 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 our guidance and supervision. In our 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.

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Acknowledgements

Firstly, I would like to express my sincere gratitude to my supervisors Dr Gufran S Khan, Associate Professor, SeNSE, IIT Delhi and Prof. Chandra Shakher, Professor, SeNSE, IIT Delhi for all of their guidance, support and inspiration for my research work during PhD. Their expertise and immense knowledge in the area of optics and innovative approach towards research is nothing short of superb. Under their supervision, I learned how to formulate and explore the research problem and find a solution to it. Whenever I came across any personal or professional hardship, they always supported and motivated me to deal with it. Their great efforts and advice helped me to learn valuable lessons which would definitely help me in my future career. My sincere thanks also goes to Prof. Stefan Sinzinger, Technical University Ilmenau, Germany for providing his valuable suggestions and guidance to carried out the research work.

I am also grateful to my thesis committee members: Prof. Joby Joseph (Department of Physics), Prof. Senthilkumaran (Department of Physics) and Prof. Kedar B. Khare, (Department of Physics), IIT Delhi for their insightful comments and encouragement, and also for the technical inputs which encouraged me to widen my research from various perspectives. I would like to thank other faculty members Dr. Satish Dubey, Prof.Subrat Kar, Head SeNSE and the concerned administrative staff for their necessary administrative support in various situations.

My sincere thanks to Dr. G Satish Reddy, Secretary and Chairman DRDO, Ms J Manjula, Distinguished Scientist and Director General (ECS) and Sh Benjamin Lionel, Outstanding Scientist and Director, IRDE (DRDO), who provided me an opportunity to join one of the premier institute of the country to carry out research work apart from my professional commitments. Without their support and guidance, it would not be possible to conduct the research. Further, sincere thanks to Sh Amitava Ghosh, Scientist G of IRDE for providing his valuable suggestion and guidance to complete my research work.

I thankful to Dr. Dali Ramu, IIT Delhi, for his support, help and inputs in my research by spending many sleepless nights and having technical discussions. Also Thanks to Mr. Lalit Mohan pant, Scientist-F at IRDE, Mr. Vinod Mishra, Technical officer at Central Scientific Instruments Organisation (CSIO) Chandigarh, Mr. M P Singh Scientist-D at IRDE, Ashish Dwivedi, Assistant manager at BARCO Electronic Systems Private Limited, Noida for their

help and support. Further, thank to lab friends Anil, Ankit, Nitin, Arjit, Deblina, Amir and other friends at IIT for their support during my PhD work. My appreciation and thanks to the staff of optical workshop,Mr.Sathish Chandra Bansal, Mr.Surender Kumar, Mr.Ramotar, and Sumit, for their instant technical and infrastructural help in very friendly way.
I owe my deepest gratitude towards my better half for her eternal support and understanding of my goals and aspirations. Her infallible love and support has always been my strength. Her patience and sacrifice will remain my inspiration throughout my life. Without her support, I would not have been able to complete much of what I have done and become who I am. It would be ungrateful on my part if I thank Sony in these few words. I am thankful to my son Aarush and Aadvit for giving me happiness during completion of the research work. A special thanks to my younger brother Vinu, sisters Ranjana and Gunjan for their love and affection.

I feel a deep sense of gratitude for my parents, (Late) Sh. P C Pant and Smt. Bharati Pant who formed part of my vision and taught me good things that really matter in life. Their infallible love and support has always been my strength. Their patience and sacrifice will remain my inspiration throughout my life. I am also very much grateful to all my family members for their constant inspiration and encouragement.

Thank you all..!!

Kamal Kishor Pant

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.

सारांश

ऑप्टिकल घटकों की कम संख्या के साथ प्रणाली के प्रदर्शन को बेहतर बनाने के लिए ऑप्टिकल उद्योग में नई डिज़ाइन प्रवृत्ति की फ़्रीफ़ॉर्म सतहें उभर रही हैं । इन सतहों को गैर-सममितीय प्रोफ़ाइल चित्रित किया जाता है और यह सतह कॉम्पैक्ट एवं हल्के भार वाले ऑप्टिकल प्रणाली को डिज़ाइन करते समय घूर्णी सममित सतहों पर अतिरिक्त लाभ प्रदान करती है । फ़्रीफॉर्म सतहों का उपयोग गैर-इमेजिंग अनुप्रयोगों जैसे कि कॉम्पैक्ट प्रोजेक्शन प्रणाली, हेडअप-डिस्प्ले, लिथोग्राफी, कम्प्यूटेशनल इमेजिंग, स्पेस ऑप्टिक्स और ऑप्टिकल माइक्रोसिस्टम्स में किया गया है । वर्तमान ऑप्टिकल डिज़ाइन की प्रवृत्ति और सटीक निर्माण प्रौद्योगिकी की उन्नति शोधकर्ताओं को इमेजिंग अनुप्रयोग में जैसे कि स्पेस ऑप्टिक्स एवं उच्च फोकस गहराई युक्त तापीय प्रतिबिंबीय प्रणाली के लिए प्रेरित कर रही है । लाभ के साथ, ऐसी जटिल सतहों के निर्माण एवं मापन में कई चुनौतियां हैं ।

आधुनिक ऑप्टिकल फैब्रिकेशन विधियां, सैद्धांतिक रूप में, जटिल फ्रीफ़ॉर्म आकृतियों को निर्मित करने में सक्षम हैं । हालांकि, इन प्रकाशीय घटकों की मेट्रोलॉजी अभी भी चुनौतीपूर्ण है और फ्रीफॉर्म सतहों पर सटीकतापूर्वक निर्माण करने के लिए एक सीमित कारक है । आधुनिक सीएनसी(CNC) मशीनों द्वारा विशिष्ट फैब्रिकेशन टॉलरेन्सेस को प्राप्त करने के लिए उपयुक्त मापन प्रणाली की आवश्यकता होती है जो कि फैब्रिकेशन त्रुटियों को कम कर सके । वर्तमान प्रोफिलोमेट्री और इंटरफेरोमेट्री आधारित मापन प्रणालियों की फ़्रीफ़ॉर्म सतहों के मापन की अपनी चुनौतियाँ एवं सीमाएं हैं ।

शेक हार्टमैन सेंसर (*एसएचएस*) की वेवफ्रंट मापन क्षमता, कम लागत, कंपन असंवेदनशील एवं नॉन-नल प्रवृत्ति होने के कारण इसे फ्रीफ़ॉर्म सतहों के मापन में लाया गया है । इन गुणों के कारण, *एसएचएस* ऑन-मशीन फ्रीफ़ॉर्म मेट्रोलॉजी के लिए उपयुक्त उम्मीदवार है जो कि फ्रीफ़ॉर्म ऑप्टिक्स के सुधारात्मक मशीनिंग के लिए मेट्रोलॉजी फीडबैक प्रदान करता है । *एसएचएस* एक कम रिज़ॉल्यूशन सेंसर है एवं इस सेंसर द्वारा मापन की गतिशील सीमा परीक्षण सतह के स्लोप द्वारा सीमित है । फ्रीफ़ॉर्म ऑप्टिक्स/वेवफ्रंट की इन सीमाओं को विशिष्ट सब-अपर्चर स्टिचिंग तकनीकी एवं स्कैनिंग *एसएचएस* कॉन्फिगरेशन के द्वारा संबोधित किया जा सकता है । अनुसंधान कार्य का लक्ष्य एक सब-अपर्चर स्टिचिंग एल्गोरिद्म एवं इसका अनुप्रयोग फ्रीफ़ॉर्म सतहों पर *एसएचएस* सेंसर आधारित मापन की तकनीक को विकसित करना होगा ।

थीसिस में अनुसंधान कार्य के लक्ष्य को प्राप्त करने के लिए निम्नलिखित प्रमुख जाँच की गई है –

- सब-अपर्चर स्टिचिंग इंटरफेरोमेट्री (SSI) आधारित तकनीकों का अध्ययन एवं इसका क्रियान्वयन गोलीय, अगोलीय एवं क्यूबिक सतहों के मापन में किया गया है।
- सब-अपर्चर स्टिचिंग एल्गोरिद्म तथा स्टिचिंग टूल बॉक्स को विकसति किया गया है जो कि यह डिज़ाइन, विनिर्माण एवं परीक्षण प्लेटफॉर्म के साथ संगत है एवं स्कैनिंग एसएचएस कॉन्फ़िगरेशन द्वारा फ्रीफ़ॉर्म सतहों का मापन में सक्षम है।
- वेटेड क्यूबिक स्लाइन आधारित एकीकरण (WCSLI) का उपयोग करके फ्रीफ़ॉर्म सतहों के स्टीप स्लोप डेटा के लिए एक बेहतर इंटिग्रेशन एल्गोरिद्म विकसित किया है तथा इसका प्रयोग बेहतर स्कैनिंग *एसएचएस* एवं सब-अपर्चर स्टिचिंग आधारित फ्रीफ़ॉर्म मेट्रोलॉजी में किया गया है।
- आईसीपी एवं आईएसएफ आधारित विधि द्वारा एक सटीक रेजिस्ट्रेशन सब-अपर्चर स्टिचिंग तकनीक की जाँच की गई है जो कि सब-अपर्चर स्टिचिंग प्रक्रिया के दौरान संरेखण संबंधी मुद्दों को संबोधित करता है।

पहला अध्याय फ्रीफ़ॉर्म ऑप्टिक्स का एक सामान्य अवलोकन प्रस्तुत करता है। गैर-इमेजिंग एवं इमेजिंग अनुप्रयोगों में उपयोग के लिए फ्रीफ़ॉर्म ऑप्टिक्स के लाभ पर प्रकाश डाला गया है। बुनियादी गणितीय पृष्ठभूमि और प्रदर्शन मूल्यांकन के साथ फ्रीफ़ॉर्म ऑप्टिक्स के डिज़ाइन में चुनौतियों पर चर्चा की गई है। फ्रीफ़ॉर्म सतहों के निर्माण के रुझानों का अध्ययन किया गया है और सटीक विनिर्माण टॉलरेन्सेज प्राप्त करने के लिए उनकी सीमाओं पर भी चर्चा की गई है। अंतिम खंड में, विभिन्न मेट्रोलॉजी तकनीकों पर एक सर्वेक्षण किया गया है।

दूसरे अध्याय में, ऑप्टिकल वेवफ्रंट के परीक्षण के लिए एसएसआई के बुनियादी सिद्धांत पर चर्चा की गई है। एसएसआई आधारित तकनीकियों का अनुप्रयोग फ्लैट एवं अगोलीय सतहों पर सर्कुलर तथा ऐनुलर सब-अपर्चर स्टिचिंग द्वारा पूर्ण फेज़ प्रोफाइल की गणना करने के लिए किया गया है। इस तकनीक का प्रयोग सीएनसी पॉलिशिंग प्रक्रिया द्वारा पॉलिश किए गए उथले क्यूबिक फ्रीफ़ॉर्म सतह के मापन में किया गया है। अंत में, सब-अपर्चर स्टिचिंग इंटरफेरोमेट्री की फ्रीफ़ॉर्म सतहों के मापन में सीमितताओं पर चर्चा की गई है।

तीसरे अध्याय में, स्लोप आधारित स्कैनिंग *एसएचएस* का उपयोग करके फ्रीफ़ॉर्म वेवफ्रंट के मापन को प्रदर्शित किया गया है। फ्रीफ़ॉर्म वेवफ्रंट की माप के लिए सब-अपर्चर स्टिचिंग तथा स्कैनिंग *एसएचएस* कॉन्फिग्रेशन पर आधारित एक विधि विकसित की गई है। स्टिचिंग एल्गोरिद्म का गणितीय मॉडल विकसित किया गया है। गणितीय मॉडल पर आधारित सिमुलेशन परिणाम प्रयोगात्मक रूप से फ्रीफ़ॉर्म

सतहों पर सत्यापित किए गए। गैर-इमेजिंग अनुप्रयोगों में फ्रीफ़ॉर्म मेट्रोलॉजी के लिए प्रस्तावित विधि एक प्रभावी दृष्टिकोण है। स्टिचिंग के दौरान मिसअलाइन्मेंट में सुधार की सटीकता बढ़ाकर, इसे इमेजिंग अनुप्रयोगों के लिए फ्रीफ़ॉर्म ऑप्टिक्स के मापन में लागू किया जा सकता है।

चौथे अध्याय में, फ्रीफ़ॉर्म सतह के स्लोप डेटा के इंटीग्रेशन के लिए स्प्लाइन आधारित तकनीकी के प्रयोग को प्रस्तुत किया है। फ्रीफ़ॉर्म सतहों के मशीनिंग के कारण इनके स्लोप डेटा में नॉइज रहता है जो कि इनके इंटीग्रेशन प्रक्रिया में त्रुटि उत्पन्न करता है। WCSLI को फ्रीफ़ॉर्म सतह के नॉइजी स्लोप डेटा के एकीकरण के लिए विकसित किया गया है। इस तकनीकी को स्कैनिंग एसएचएस एवं सब-अपर्चर स्टिचिंग द्वारा फ्रीफ़ॉर्म वेवफ्रंट के प्रायोगिक रूप से मापन में किया गया है।

पांचवें अध्याय में, सब-अपर्चर स्टिचिंग प्रक्रिया के दौरान उत्पन्न लैटरल मिसएलाइन्मेंट के निम्निकरण के लिए पंजीकरण आधारित योजना प्रस्तुत की गई है। अध्याय के पहले खंड में, एक आईसीपी आधारित पंजीकरण योजना प्रस्तावित है, जिसमें स्कैनिंग प्रक्रिया के दौरान उत्पन्न लैटरल मिसएलाइन्मेंट जो कि एसएचएस द्वारा मापित डेटा के एक सैम्पल के पूर्णांक क्रम में हो, को कम किया गया है। अगले खंड में, आईएसएफ पर आधारित एक सटीक पंजीकरण योजना प्रस्तुत की है, जिसमें अप-सैम्पल्ड क्रॉस-कोरिलेशन तकनीकी का प्रयोग कर एसएचएस द्वारा मापित डेटा के सब-सैम्पल्ड आर्डर के लैटरल मिसएलाइन्मेंट को कम किया गया है जो कि स्टिचिंग प्रक्रिया को भी संशोधित करता है।

छठा अध्याय शोध कार्य, लाभ और स्कैनिंग एसएचएस आधारित फ्रीफ़ॉर्म मेट्रोलॉजी और अनुसंधान कार्य के भविष्य के दायरे से निकाले गए निष्कर्ष प्रस्तुत करता है।

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List of Abbreviations

CNC	Computer numerically controlled
SHS	Shack-Hartmann sensor
SSI	Subaperture stitching interferometry
WCSLI	Weighted cubic spline based least square integration
ICP	Iterative closest point
ISF	Intrinsic surface feature
PAL	Progressive addition lens
LED	Light emitting diode
HUD	Headup display
SMS	Simultaneous multiple surface based method
LWIR	Long wave infra-red
PDE	Partial differential equation
FTS	Fast tool servo
STS	Slow tool servo
SPDT	Single point diamond turning
MRF	Magnetorhelogical finishing
ELID	Electrolytic in-process dressing
CCP	Computer controlled polishing
CMM	Coordinate measuring machine
PGI	Phase grating interferometer
PV	Peak to valley
RMS	Root mean square
AFM	Atomic force microscopy
NANOMEFOS	Nanometer accuracy non-contact measurement of freeform optical surfaces
CGH	Computer generated hologram
PNL	Partial Null Lens
TWI	Tilted wave interferometry
MWLI	Multi wavelength interferometry
SS-OCT	Swept source optical coherence tomography
PMD	Phase measuring deflectometry
VON	Variable optical null

AO	Alternating optimization
LS	Least square
SSAS	Spherical subaperture stitching
NA	Numerical aperture
TS	Transmission sphere
CCD	Charge couple devices
CSLI	Cubic spline based least square integration
FT	Fourier transform
IFT	Inverse Fourier transform
IRLS	Iteratively robust least square
FFT	Fast Fourier transform