SOME NOVEL APPLICATIONS OF DIGITAL SPECKLE PATTERN INTERFEROMETRY AND DIGITAL HOLOGRAPHIC INTERFEROMETRY

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OCTOBER, 2016

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by

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Submitted

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

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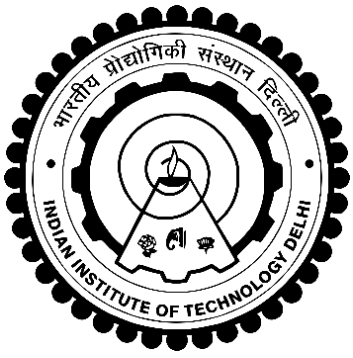

INDIAN INSTITUTE OF TECHNOLOGY DELHI

OCTOBER, 2016

DEDICATED

TO

MY FAMILY

WHO ENCOURAGED AND SUPPORTED ME TO DO
WHATEVER I WANTED TO DO, AND BE
WHATEVER I WANTED TO BE

CERTIFICATE

This is to certify that the thesis entitled **"SOME NOVEL APPLICATIONS OF DIGITAL SPECKLE PATTERN INTERFEROMETRY AND DIGITAL HOLOGRAPHIC INTERFEROMETRY"** being submitted by **Mr. MANOJ KUMAR** to the Indian Institute of Technology Delhi for the award of the degree of "**DOCTOR OF PHILOSOPHY**", is a record of the authentic research work carried out by him under our supervision and guidance. He has fulfilled all the requirements for submission of this thesis, which to the best of my knowledge has reached the required standard.

The material contained in this thesis has not been submitted in part or full to any other University or Institute for the award of any other degree.

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ACKNOWLEDGEMENTS

I owe thanks to several people who helped, supported and inspired me in many ways at different stages of my Ph.D. and made it an unforgettable experience for me.

First and the foremost, I would like to extend my special appreciation and sincere gratitude to my research supervisor **Prof. Chandra Shakher** who has introduced me to Speckle Metrology and Digital Holography – the intriguing field of science and engineering. The work reported in this thesis would not have been possible without his efficient and erudite guidance, continuous support, advice, inspiration, encouragement and motivation throughout my Ph.D. I successfully overcame many difficulties and learned this *beautiful field of metrology* under his guidance. His integral view on research and his mission for providing high-quality work has made a deep impression on me and I hope to continue to work with his noble thoughts. I also, express my profound indebtedness to him for the time he took out from his hectic schedule to guide me during the course of the thesis. He would have never accepted anything less than my best efforts, and for that, I thank him.

My special words of thanks should also go to my research supervisor **Dr. Gufran S. Khan**. His continuous support, guidance, cooperation, encouragement and motivation have always kept me going ahead. I owe a lot of gratitude to his scientific inputs, personal helps and friendly nature and I feel privileged to be associated with a person like him.

I am highly grateful to my Students Research Committee (SRC) members, **Prof. A.L. Vyas**, **Prof. M.R. Shenoy**, and **Prof. D.S. Mehta**, for their constructive comments and helpful suggestions during my progress report presentations.

A true friend is someone who reads the song in your heart and can sing it back to you, when you have forgotten the actual words. I have found such a friend in the form of **Ms. Shilpi Agarwal**. I cannot find the correct words to thank for her priceless and most prestigious support during my research work. She is my close friend and brilliant colleague who inspired me over the years. She was always there for me in my failures, weird situations and tolerated my frustrations and nonsenses but supported me throughout this period. I had shared many memorable moments and will always cherish these moments spent with her. I remember, knowingly or unknowingly I made her irritate many times but she never complained. Thank you for just being there when I need you.

I would like to express my deepest thanks and acknowledgements with gratitude and affection to fellow lab-mates **Dr. Gyanendra Sheoran**, **Dr. Shobhna Sharma**, **Mr. Varun Kumar**, **Ms. Sruthi Prasood**, **Ms. Monika**, **Mr. Avijit Prakash**, and **Mr. Pranav Kumar Pandey** for their support and co-operation as colleagues, who helped me in many ways at different stages of my thesis work in the Laser Applications and Holography Laboratory, IDD Centre, Indian Institute of Technology Delhi.

I appreciate and respect to **Dr. Vishal Srivastava** and **Dr. Mohd. Inam** for their moral support, valuable suggestions and sincere encouragement. I owe special thanks to **Dr. Vishal Srivastava** for discussions regarding image processing and other scientific issues.

I want to thanks my special friends **Mr. Mahipal Bhumbla**, **Mr. Navdeep Phogat, Mr. Vikas Malik**, **Mr. Anil Malik**, **Mr. Sanjeet Kumar**, and **Mr. Anuj Prashar** with whom I spent very special time while playing, running, chatting, in any order and for all the fun we have had in the last few years during my stay in Shivalik Hostel. I cannot forget these friends because they went through my hard times with me, cheered me on and celebrated

each accomplishment. I am indebted to these friends for providing a stimulating and fun filled environment.

Words are short to express my deep sense of gratitude towards my following friends, **Ms. Ankita Gaur**, **Ms. Neelam Sehrawat**, **Mr. Tajber Singh**, **Mr. Rammurthy Godisela**, **Ms. Shweta Sehgal**, **Mr. Dinesh Bhardwaj**, **Mr. Asim Mahakula**, **Mr. Sharad Gupta**, **Mr. Yogesh Gupta**, **Mr. Naveen Bhardwaj**, and **Mr. Pankaj Mittal** with whom I shared my life experiences and they gave me reasons to go ahead with my work. These friends are used to talk regularly and help me to overcome the inevitable moments of demoralization.

Thanks are also to the technical staff of the workshop in Instrument Design Development Centre, IIT Delhi for the help rendered by them. I am thankful to **Mr. Surinder Singh** and **Mr. S.K. Bansal** for extending their valuable help at times.

The equipment used in the experiment which was purchased from Department of Science and Technology (**DST)**, Govt. of India project is greatly acknowledged.

Last but not the least, I express deep sense of gratitude and loving thanks to **my parents** for their love, patience and inspiration in various stages of my research work and lifting me uphill this phase of life. I am grateful to my brother **Mr. Sundeep** and sister **Ms. Urmila** for their unending encouragement and helpful suggestions throughout this endeavor. Without their support and unconditional help, I would have never come so far.

Finally, I thank the almighty of God for giving me power to believe in myself and fulfil my dreams. There is no way to express how much it meant to me to have been a member of Laser Applications and Holography Laboratory.

Thank you all!

Date: **Manoj Kumar**

ABSTRACT

Optical interferometric techniques have proved enormous capabilities and potentials in scientific, engineering and industrial measurements. The interferometric techniques became more powerful and easy to implement after the invention of laser and holography. Holography and speckle interferometry added new dimensions in the interferometry by offering the capability to characterize rough mechanical surfaces with submicron accuracy and made it a powerful tool for the scientists and engineers to solve many problems of scientific and industrial importance. Further development in analog and digital electronics, electronic imaging devices, high speed digital computers and reliable image processing software has revolutionized optical measurement techniques. The optical interferometric techniques have become automated, effective, and easier to visualize the measurement results.

Digital speckle pattern interferometry (DSPI) and digital holographic interferometry (DHI) are widely used promising evaluation optical measurement techniques. Both these techniques are developed independently but can be regarded as two experimental approaches of the same concept of interferometry for transparent, opaque and diffusely scattering objects. The goal of this thesis is to design and develop the DSPI and DHI systems for investigating the various scientific and industrial measurements.

The thesis is divided into six chapters:

Chapter 1 outlines the detailed description of DSPI and DHI and their applications in metrology. A review of phase extraction techniques and proposed phase extraction method, i.e. Riesz transform and monogenic signal, is described in detail. A brief description of

digital holography including the numerical reconstruction of digitally recorded holograms is provided in the next section. A brief outline of the research contribution and scope of this research work is presented at the end of the chapter.

Chapter 2 provides the application of DSPI for the measurement of temperature and evaluation of temperature profile of diffusion, premixed and partially premixed flames obtained from butane torch burner under the influence of uniform magnetic field, upward-decreasing magnetic gradient field and upward-increasing magnetic gradient field.

Chapter 3 demonstrates the use of digital speckle pattern shearing interferometry (DSPSI) where the shear is created by volume phase holographic grating to measure the temperature and temperature profile of diffusion flame (candle flame). The proposed DSPSI system is simple, compact, requires low mechanical stability and less vibration sensitive.

Chapter 4 describes an application of DSPI for the measurement of deformations and strain-field distributions developed in cortical bone around orthodontic miniscrew implants of different diameters and lengths inserted into the human maxilla is presented.

Chapter 5 demonstrates the application of Lensless Fourier transform digital holographic interferometry (LLFTDHI) to study the effect of moisture on the dimensional changes of different samples of wood. Further, investigations are done to determine the induced strain due to the shrinkage of wood and to measure the hygroscopic shrinkage coefficients during the convective drying process of differently treated seasoned woods.

Chapter 6 summarizes the main points of research work and also some potential further development scopes related to our findings in optical metrology.

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LIST OF ABBREVIATIONS

Abbreviation	Definition
DSPI	Digital speckle pattern interferometry
DHI	Digital holographic interferometry
DH	Digital holography
LLFTDH	Lensless Fourier transform digital holography
LLFTDHI	Lensless Fourier transform digital holographic interferometry
ESPI	Electronic speckle pattern interferometry
A/D	Analog-to-digital
CCD	Charge-couple device
CMOS	Complementary metal-oxide semiconductor
HOE	Holographic optical element
FFT	Fast Fourier transform
IFFT	Inverse fast Fourier transform
SPS	Spatial phase-shifting
TPS	Temporal phase-shifting
PZT	Piezoelectric transducer
FTM	Fourier transform method
CWT	Continuous Wavelet transform
HT	Hilbert transform
EMD	Empirical mode decomposition
SNR	Signal-to-noise ratio
Re	Real function
Im	Imaginary function
DSPSI	Digital speckle pattern shearing interferometer

FEM	Finite element method
CT	Computed tomography
DIC	Digital image correlation
WFT	Windowed Fourier transform
WFF	Windowed Fourier filtering
MC	Moisture content

LIST OF SYMBOLS

σ_o	Average diameter of objective speckle
σ_s	Average diameter of subjective speckle
d_0	Average diameter of a circular illuminated patch of the diffused object
d	Distance between object and image plane
λ	Wavelength of laser light used
F	*f*-number of the imaging lens
M	Magnification of the imaging lens
$A(x, y, z)$	complex amplitude of the object wave at the point $O(x,y,z)$
a_n	Amplitude of the n^{th} scattered elementary wave
ϕ_n	Phase of the n^{th} scattered elementary wave
$p(I)$	Probability distribution of speckle pattern
I	Intensity of the speckle pattern
$\langle I \rangle$	Average intensity of the speckle pattern
σ	Standard deviation of speckle pattern
γ	Normalized standard deviation of speckle pattern, or speckle index
a_o	Amplitude of the object wave
ϕ_o	Phase of the object wave
a_r	Amplitude of the reference wave
ϕ_r	Phase of the object reference wave
I_o	Intensities of the object wave
I_r	Intensities of the reference wave

$\phi = (\phi_o - \phi_r)$	Random phase of the speckle interferogram
$\Delta\Phi$	Additional phase difference introduced by either object deformation or by refractive index fluctuation
$I(x, y)$	Resultant intensity distribution of two speckle interferograms,
k_1	Propagation vector of illumination beam
k_2	Propagation vector of observation beam
k_s	Sensitivity vector
d_x, d_y, d_z	Deformation vector of a point *O*(*x*, *y*) on the object surface along *x*-, *y*-, *z*-directions respectively
e_x, e_y, e_z	Unit vectors in *x*, *y*, *z*- directions respectively
θ_{xz}	Angle between the illumination and observation vectors in the *x*, *z*-plane
ψ_0	Phase of vibration of the object
ω	Angular frequency of vibration
J_0	Zeroth-order Bessel function
a	Amplitude of vibration
Δx	Lateral shear in *x*-direction
γ_0	Amplitude modulation term
α_i	Average value of relative phase shift for i^{th} exposure
ξ	Spatial frequency along *x*-direction
ξ_0	Spatial carrier
$\mathrm{I}(\xi, y)$	Fourier transform of $I_0(x, y)$
$C(\xi - \xi_0, y)$	Fourier transform of $c(x, y)\exp(i2\pi\xi_0 x)$
$C^*(\xi - \xi_0, y)$	Fourier transform of $c^*(x, y)\exp(-i2\pi\xi_0 x)$

$W(b', a, \theta)$	Wavelet transform coefficient
$\psi(X)$	Mother wavelet
$R[.]$	Riesz operator
$\hat{H}(k)$	Transfer function of the Riesz transform
$I_x(x, y)$	Riesz transform components on *x*- axis
$I_y(x, y)$	Riesz transform components on *y*- axis
R_x	Spatial representation of the Riesz kernel on *x*- axis
R_y	Spatial representation of the Riesz kernel on *y*- axis
$S_M(x, y)$	3-D monogenic signal
ϑ	Orientation between two Riesz transform components
$f_{\max}$	Maximum spatial frequency of the CCD/CMOS detector
Q	Fringe spacing
$\theta_{\max}$	Maximum angle between the object and the reference beams
ΔX	Pitch of the CCD/CMOS detector
X_0	X coordinate in object plane
Y_0	Y coordinate in object plane
X_H	X coordinate in hologram plane
Y_H	Y coordinate in hologram plane
X_I	X coordinate in image plane
Y_I	Y coordinate in image plane
O	Complex amplitude of the object wave
O^*	Complex conjugate of the object wave
R	Complex amplitude of the reference wave
R^*	Complex conjugate of the reference wave
$I(X_H, Y_H)$	Intensity distribution of the interference pattern at hologram plane

$I(p,q)$	Digital hologram
ΔX_H	Sampling interval along X-axis in hologram plane
ΔY_H	Sampling interval along Y-axis in hologram plane
ΔX_I	Sampling interval along X-axis in image plane
ΔY_I	Sampling interval along Y-axis in image plane
$L \times B$	Dimensions of CCD/CMOS detector
$M \times N$	Number of pixels in CCD/CMOS detector
$O(X_I, Y_I)$	Complex amplitude of reconstructed object wave in image plane
ρ'	Distance between a point in hologram plane and a point in the image plane
$R(p,q)$	Digitized reference wave
$\phi(m,n)$	Phase distribution of reconstructed object wavefield
$\Delta\Phi(m,n)$	Phase difference of reconstructed object wavefields
$n(r)$	Refractive index of the medium
n_o	Refractive index of the air (reference state)
T	Temperature to be calculated
T_0	Temperature at the reference condition (Room temperature)
P	Atmospheric pressure
R	Universal gas constant
A	Molar refractivity of air at 632.8 nm (4.606×10^{-6} m^3/mol)
χ	Magnetic susceptibility (subscripts *f* for fuel and *ox* for oxygen)
F_{mag}	Magnetic body force
B	Magnetic induction (Tesla)
$\frac{dB}{dz}$	Magnetic gradient field in z-direction
μ_0	Magnetic permeability of free space (Henry per meter)

Grm	Magnetic Grashoff number
Frm	Magnetic Froude number
R_e	Reynolds number
ρ	Density of fuel (butane) (Kg/m^3)
ν	Viscosity of the fuel (N-s/m^2)
u	Fuel velocity (m/s)
b	Diameter of burner tube (m)
l'	Distance between magnetic poles (m)
s	Amount of shear
α	Angle of incident light on the volume phase holographic grating
β	Angle in which the first order is diffracted
ε	Strain
f	Focal length of the imaging lens