OPTICAL METROLOGY BY CIRCULAR GRATING TALBOT INTERFEROMETER AND DIGITAL HOLOGRAPHY

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by

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DEDICATED

TO

TWO MEN IN MY LIFE

(Success is in my side, because I have you two by my side)

My father - for his endless love, support and encouragement

My Husband - for being my inspiration, his remarkable patience and unwavering love who dragged me even through kicking most of the way

CERTIFICATE

This is to certify that the thesis entitled, "**OPTICAL METROLOGY BY CIRCULAR GRATING TALBOT INTERFEROMETER AND DIGITAL HOLOGRAPHY**" being submitted by **Ms. SHILPI AGARWAL**, to the Indian Institute of Technology Delhi, for the award of the degree of **"DOCTOR OF PHILOSOPHY"** is a record of the bonafide research work carried out by her under my supervision and guidance. She 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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ABSTRACT

Optics relates to the generation, amplification, propagation, reception, modification and modulation of light. In brief, *Optics* is science, technology and engineering with light. Measurement techniques based on properties of light come under *Optical Metrology*. Optical interferometric techniques provide improved accuracy/precision over mechanical methods of measurement; such techniques provide non-destructive testing (NDT), have higher resolution and dynamic range and allow the recognition of flaws and defects in materials and components. At present many optical interferometric measurement and non-destructive testing techniques, like classical interferometry, shearing interferometry, Moiré interferometry, fringe projection technique, Lau phase interferometry, holographic interferometry, speckle pattern interferometry and Talbot interferometry etc. are available. Optical interferometric techniques for measurement and NDT are sensitive to environmental perturbations, while from the industrial perspective one need a method which is accurate, cost-effective and capable to work in industrial environment.

Talbot interferometer has been used for the measurement of displacement, collimation, focal length, refractive index, low frequency vibrations and temperature etc. In this thesis, three new applications of circular grating Talbot interferometer are investigated. Further, digital holographic interferometry is investigated for measurement of temperature and temperature profile of micro flame under the influence of magnetic field.

The thesis is organized in six chapters:

Chapter I provide a brief introduction of Talbot interferometer and the detailed description of linear grating and circular grating Talbot interferometer under plane wave and spherical wave

illumination. This chapter also provides the outline of the research work presented in this thesis.

Chapter II presents the investigations of in-plane displacement measurement by using circular grating Talbot interferometer. The measurement of shift of fringe position from the grating center is used to measure the in-plane displacement. This method can be used as an alternative method of measurement of in-plane displacement.

Chapter III gives the experimental investigations of the effect of magnetic field on temperature and temperature profile of butane diffusion flame, premixed flame and partially premixed flame (with 50% air) using circular grating Talbot interferometer. This investigation is useful to improve the combustion process and increase the combustion efficiency.

Chapter IV presents the measurement of the temperature and temperature profile of wick-stabilized micro-diffusion flame under the influence of magnetic field using circular grating Talbot interferometer. In this chapter the phase information is extracted by Hilbert transform to obtain the full field data from a single interferogram.

Chapter V deals with a method for measurement of temperature and temperature fluctuations in wick-stabilized micro diffusion flame using digital holographic interferometry. Digital holography is ideally suited to study micro flames.

Chapter VI described the Talbot effect/self-imaging effect for cell level imaging of biological specimens (Onion epidermis cell, Red blood cell) using linear grating. Experimental results show that this type of system can be used for clinical applications.

सार

प्रकाशिकी पीढ़ी, प्रवर्धन, प्रसार, स्वागत, संशोधन और प्रकाश के मॉड्यूलेशन से संबंधित है। संक्षेप में, प्रकाशिकी विज्ञान के साथ विज्ञान, प्रौद्योगिकी और इंजीनियरिंग है। प्रकाश की गुणों के आधार पर मापन तकनीक ऑप्टिकल मेट्रोलॉजी के अंतर्गत आती है। ऑप्टिकल इंटरफेरोमेट्रिक तकनीक माप के यांत्रिक तरीकों पर बेहतर सटीकता / सटीकता प्रदान करती है; ऐसी तकनीकें गैर-विनाशकारी परीक्षण (एनडीटी) प्रदान करती हैं, उच्च रिज़ॉल्यूशन और गतिशील रेंज होती है और सामग्री और घटकों में त्रुटियों और दोषों की पहचान की अनुमति देती है। वर्तमान में कई ऑप्टिकल इंटरफेरोमेट्रिक मापन और गैर-विनाशकारी परीक्षण तकनीकों, जैसे शास्त्रीय इंटरफेरमेट्री, कतरन इंटरफेरमेट्री, मोइरे इंटरफेरेट्री, फ्रिंज प्रक्षेपण तकनीक, लॉउ चरण इंटरफेरमेट्री, होलोग्रफ़िक इंटरफेरमेट्री, स्क्लेल पैटर्न इंटरफेरमेट्री और टैलबोट इंटरफेरमेट्री आदि उपलब्ध हैं। माप और एनडीटी के लिए ऑप्टिकल इंटरफेरोमेट्रिक तकनीक पर्यावरण संबंधी परेशानियों के प्रति संवेदनशील हैं, जबकि औद्योगिक परिप्रेक्ष्य से किसी को एक ऐसी विधि की आवश्यकता होती है जो सटीक, लागत प्रभावी और औद्योगिक वातावरण में काम करने में सक्षम हो।

टैलबोट इंटरफेरोमीटर का उपयोग विस्थापन, कोलाइमन, फोकल लम्बाई, अपवर्तक सूचकांक, कम आवृत्ति कंपन और तापमान इत्यादि के माप के लिए किया गया है। इस थीसिस में, सर्कुलर ग्रेटिंग टैलबोट इंटरफेरोमीटर के तीन नए अनुप्रयोगों की जांच की जाती है। इसके अलावा, चुंबकीय क्षेत्र के प्रभाव में सूक्ष्म लौ के तापमान और तापमान प्रोफाइल के माप के लिए डिजिटल होलोग्राफिक इंटरफेरेट्री की जांच की जाती है।

थीसिस छह अध्यायों में आयोजित किया जाता है:

अध्याय I मैं टैलबोट इंटरफेरोमीटर का एक संक्षिप्त परिचय प्रदान करता हूं और रैखिक ग्रेटिंग और सर्कुलर ग्रेटिंग टैलबोट इंटरफेरोमीटर का विस्तृत विवरण विमान लहर और गोलाकार लहर रोशनी के तहत प्रदान करता हूं। यह अध्याय इस थीसिस में प्रस्तुत शोध कार्य की रूपरेखा भी प्रदान करता है।

अध्याय II सर्कुलर ग्रेटिंग टैलबोट इंटरफेरोमीटर का उपयोग करके इन-प्लेन विस्थापन माप की जांच प्रस्तुत करता है। ग्राउटिंग सेंटर से फ्रिंग स्थिति की शिफ्ट का माप इन-प्लेन विस्थापन को मापने के लिए किया जाता है। इस विधि को इन-प्लेन विस्थापन के माप के वैकल्पिक तरीके के रूप में उपयोग किया जा सकता है।

अध्याय III परिपत्र ग्राउटिंग टैलबोट इंटरफेरोमीटर का उपयोग करके ब्यूटेन प्रसार आग, प्रीमिस्ड लौ और आंशिक रूप से प्रीमिस्ड लौ (50% हवा के साथ) के तापमान और तापमान प्रोफ़ाइल पर चुंबकीय क्षेत्र के प्रभाव की प्रयोगात्मक जांच देता है। यह जांच दहन प्रक्रिया में सुधार और दहन दक्षता में वृद्धि के लिए उपयोगी है।

अध्याय IV परिपत्र ग्राउटिंग टैलबोट इंटरफेरोमीटर का उपयोग करके चुंबकीय क्षेत्र के प्रभाव में विक-स्थिरीकृत माइक्रो-प्रसार फ़्यूम के तापमान और तापमान प्रोफ़ाइल के माप को प्रस्तुत करता है। इस अध्याय में चरण जानकारी हिल्बर्ट ट्रांसफॉर्म द्वारा एक इंटरफेरोग्राम से पूर्ण फ़ील्ड डेटा प्राप्त करने के लिए निकाला जाता है।

अध्याय V डिजिटल होलोग्रफ़िक इंटरफेरमेट्री का उपयोग करते हुए विक-स्थिरीकृत माइक्रो प्रसार फ़्लेम में तापमान और तापमान में उतार-चढ़ाव के माप के लिए एक विधि से संबंधित है। डिजिटल होलोग्राफी आदर्श रूप से सूक्ष्म आग का अध्ययन करने के लिए उपयुक्त है।

अध्याय VI ने रैखिक समानांतर तारों का समूह का उपयोग कर जैविक नमूने (प्याज एपिडर्मिस सेल, लाल रक्त कोशिका) के सेल स्तर इमेजिंग के लिए टैलबोट प्रभाव / स्वयं इमेजिंग प्रभाव का वर्णन किया। प्रायोगिक परिणामों से पता चलता है कि इस प्रकार की प्रणाली का उपयोग नैदानिक अनुप्रयोगों के लिए किया जा सकता है।

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a	Grating pitch
λ	Wavelength of the laser light
Z_T	Talbot distance
K	Integer
p/q	Fractional integer
ΔZ	Distance of fractional Talbot image
G1	First grating
G2	Second grating
(x, y, z)	Cartesian co-ordinate
$u_{1Before}$	Amplitude distribution (Field) before first grating
k	Propagation vector
i	Imaginary unit ($\sqrt{-1}$)
g_1	Transmittance of grating G1
m	Grating G1 order
C_m	Fourier expansion coefficient of m order grating
$u_0(x, y)$	Two dimensional object transmittance function

u_{1After}	Amplitude distribution (Field) after first grating
z_1	Distance between grating G1 and object plane
$u_{2Before}$	Amplitude distribution (Field) before second grating
g_2	Transmittance of grating G2
n	Grating G2 order
C_n	Fourier expansion coefficient of n order grating
z_2	Distance between grating G2 and object plane
u_{2after}	Amplitude distribution (Field) after second grating
M	Constant
C	Constant phase distribution of wavefront representation
I	Intensity distribution
$u^*_{2\,After}$	Complex conjugate of amplitude distribution (Field) after second grating
R	Distance between grating G1 and point source
r, φ	Polar co-ordinates of grating G1 plane
r	Radial location of any point on the grating
$2A$	Diameter of the circular grating
g_r	Fourier exponential series expression for grating transmittance

ϕ	Phase
D	Distance between grating G1 and G2
r', φ'	Polar co-ordinates of grating G2 plane
J_0	Zero order Bessel function
ε_x	Difference between grating G1 and G2 center
N	Constant coefficient under Dirac Delta function
Δx	Displacement value
x_f	Final position of point
x_i	Initial position of point
l	Integer (for the value of number of ring from grating center)
l'	Integer (for the value of number of ring from grating center)
$(1+\alpha)$	Change in pitch along the y-axis after deflection
$(1+\beta)$	Change in pitch along the z-axis after deflection
m′	Fringe number
ψ	Angle of deflection
Z_k	Distance between the object (burner) and second grating
n_m	Refractive index of medium

T_0	Temperature at the reference condition
n_0	Refractive index at the reference condition (air)
P_{atm}	Atmospheric pressure
A_m	Molar refractivity of air at 632.8 nm
R_g	Universal gas constant
F	Magnetic force
χ	Susceptibility of the chemical species
H	Magnetic field strength
a_h	Height of the micro flame
W_f	Width of micro flame
t_1	Characteristic time of travel from the burner exit to the bottom of the flame
d	Diameter of the burner tube
u_e	Fuel exit velocity at the burner port
u_d	Characteristic molecular diffusion velocity
l_D	Characteristic diffusion length
D_w	Diameter of wick
L_f	Length of Flame

L_b	Overlapping length of wick and flame
HT	Hilbert transform
$u(x)$	Real function
$z(x)$	Complex analytic signal
$l(x, z)$	Path length travelled by the light beam inside the axisymmetric temperature field
$\Delta n(r)$	Change in refractive index inside the flame
R_1	Maximum radial distance inside the flame
Q_f	Volumetric flow rate of fuel (m^3/sec)
T_m	Maximum flame temperature
S	Molar stoichiometric air-fuel ratio
Xo_2	Mole fraction of oxygen in air
m_f	Total fuel mass flow rate
C_p	Specific heat of gas at constant pressure
K	Thermal conductivity
s	Mass oxygen to fuel stoichiometric ratio
T_{vap}	Vaporization/boiling point of wax
N_a	Avogadro number

g_l	Lande's g-factor
μ_b	Bohr magneton
k	Boltzmann constant
S_i	Total electron spin
m_i	Molecular weight of species i
f_{max}	Maximum spatial frequency
Q	Fringe spacing
θ_{max}	Maximum angle between the object and reference wave
X_O	X-coordinate in object plane
Y_O	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
$O(X, Y)$	Object wave
$R(X,Y)$	Reference wave
$H(X,Y)$	Intensity distribution at hologram plane

$L \times B$	CCD rectangular aperture dimension containing
$M \times N$	Number of pixels on CCD sensor
ΔX_H	Sampling interval along X axis in the hologram plane
ΔY_H	Sampling interval along Y axis in the hologram plane
ρ	Distance between a point in the hologram plane and a point in the image plane
ΔX_I	Sampling interval along X axis in the image plane
ΔY_I	Sampling interval along Y axis in the image plane
$R(p,q)$	Digitized reference wave
$H(p,q)$	Digitized recorded intensity
ΔX_I , ΔY_I	Pixel sizes in the reconstructed image
[S]	Area matrix
a_p	Interval between the measured pixel
$\Delta\phi$	Phase difference
B	Magnetic induction (Tesla)
μ_0	Magnetic permeability of free space (Henry/meter)
κ_a	Volumetric susceptibility of air

κ_f	Volumetric susceptibility of flame
κ_w	Volumetric susceptibility of molten wax near the wick
P_{af}	Pressure at interface of surrounding air and flame
P_{fw}	Pressure at the interface of flame and molten wax
$A(x)$	Background intensity distribution
B	Constant
P	Cauchy principal integral
n_p	Refractive index of polystyrene bead