Optical Metrology and NDT
ME-5304, C’2019
https://users.wpi.edu/~cfurlong/me-593n.html
M and W: 1:00-1:50 pm, HL-031

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NEST - NanoEngineering, Science, and Technology
CHSLT - Center for Holographic Studies and Laser micro-mechaTronics
Mechanical Engineering Department
Worcester Polytechnic Institute

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ME-593 / ME-5304
Laser metrology and Nondestructive Testing (NDT)

Term C’2019

Lectures: M and W, 1:00-2:50 pm
HL-031

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COURSE DESCRIPTION

Demands for increased performance and efficiency of components in the nano/micro-, meso-, and macro-scales, impose challenges to their engineering design, study, and optimization. These challenges are compounded by multidisciplinary applications to be developed inexpensively in short time while satisfying stringent design objectives. As a consequence, effective quantitative engineering methodologies, such as optical techniques, are frequently used in the study and optimization of advanced components and systems.

In this course, modern laser metrology techniques are discussed and their practical applications to solve problems, with emphasis on nondestructive testing (NDT), are illustrated with laboratory demonstrations. Topics covered include wave and Fourier optics, classic and holographic interferometry, speckle techniques, solid-state lasers, fiber optics, CCD cameras, computer vision, camera calibration methods, and image processing and data reduction algorithms as required in quantitative fringe analysis. Detail examples of nondestructive testing and coherent optical metrology in solid mechanics, vibrations, heat transfer, electromagnetics, and reverse engineering are given.

Students are required to work on projects depending on their background and interests.

Recommended background: mechanics, materials, physics, knowledge of a high-level computer programming language.
Textbook

Hardcover: 744 pages
Publisher: CRC Press; 1 edition (February 25, 2009)
Language: English
ISBN-10: 0849337607
Recommended Textbook

Handbook of Holographic Interferometry: Optical and Digital Methods

Hardcover: 554 pages
Publisher: Wiley-VCH; 1 edition (January 31, 2005)
Language: English
ISBN-10: 3527405461
Recommended Textbook: optics background

Hardcover: 680 pages
Publisher: Addison Wesley; 4 edition
(August 12, 2001)
Language: English
ISBN-10: 0805385665
General information

Review course overview: see handout

Homework, due next Class:

• Reading assignment:
  Chapter 1 of Yoshizawa: Light Sources

• Homework assignment:
  See website of our course:
  https://users.wpi.edu/~cfurlong/me-593n.html
General information

Office hours (TBD after reviewing your schedule information):

In the meantime:

-> 2:00 to 5:00 pm Thursdays <-
Motivation: production cycle with CAD/CAE/CAM support

Original need:

Need for experimental:

- Computer-aided process planning
- Computer-aided scheduling, materials requirements, shop floor control

Motivation:

- Original need
- Product concept
- Design engineering
- Drafting
- Process planning
- Scheduling
- Manufacturing
- Quality control
- Order new equip. & tools
- Production
- Need for experimental verifications
Multiphysics FE modeling: need for experimental validations

e.g., multi-physics modeling of the package of a computer chip

Computational domain

- Plastic package
- Silicon die
- Die attach
- Cu leads
- Air gap between package and board

Computed temperature distribution

Fluid + heat + structural effects are modeled
Measurement of shape and deformations at different scales

Computer-Aided Optical Metrology: full-field-of-view non-contact capabilities

**Macroscale**

**Mesoscale**

**Microscale** and **Nanoscale**
The word "holograph" comes from "holo" meaning entire or whole and "graph" meaning writing, **so a hologram is the entire writing or the entire information.**
Classic Holographic Interferometry

Recording and reconstruction of a hologram

Reconstruction

Virtual object

Reference beam

Hologram

θ
Applications: NDT of structures

Cooling tower A

Cooling tower B
Applications: NDT of structures

Study of vibrations in turbine blades: Elinevskii et al., 1976
Applications: NDT in art conservation

Applications: fluid flow investigations

Phase-Stepped Holographic Interferometry

Pulsed Laser Recording

Phase-Stepped Interferograms

Blade Cascade

Projection

Flow direction

Digital Evaluation Density Pixel Map
Applications: fluid flow investigations

Holographic interferometry can be applied to the study of heat, mass, and momentum transfer phenomena. Unwrapped phase: related to properties of the fluid flow.

Wrapped phase

Fringe pattern
Applications: SAR interferometry

SAR interferogram of undulating terrain: Ghiglia et al., 1998

Recovered phase

Topography
Digital holography: high-speed measurements

**Recording**

Object beam

Illumination beam

Reference beam

CCD camera

Digitally recorded hologram

**Reconstruction by application of numerical methods:**

- Fresnel integral
- Convolution
- Spatial or phase-shifting methods
Scattering + diffraction + absorption of light waves

The complex amplitude of the scattered light, $F_o$, at point $p$, can be predicted using the Kirchoff integral:

$$F_o = \frac{1}{4\pi} \left\{ \iint_{s} \frac{1}{r} \exp(-jkr) \nabla U \cdot dS - \iint_{s} \nabla \left[ \frac{1}{r} \exp(-jkr) \right] \cdot dS \right\}$$

Imaging the scattering and absorption of light allows quantification of physical quantities.

Light scattering diagram: $\lambda$ is the wavelength of the light source, $L$ is the dimension of the domain.

- $\lambda / L$:
  - $1.0$
  - $0.2$
  - $0.1$

- $K_i$ (Direction of illumination)

- $\log(\overline{F_o F_o^*})$
  - $0$
  - $1.0$
  - $0.1$
  - $0.01$
  - $0.001$

- $\theta$ (Angle of scattering): $0^\circ, 30^\circ, 60^\circ, 90^\circ, 120^\circ, 150^\circ, 180^\circ$
**Lensless digital holography**

Principle of operation: numerical reconstruction of digital holograms

Numerical reconstruction of intensity and phase at any plane along the direction of light propagation:

**Complex light distribution:**

\[
a(\xi, \eta) = (I_1 - I_3) + i(I_4 - I_2)
\]

**Rayleigh-Sommerfeld integral:**

\[
a'(x, y) = \frac{1}{i\lambda} \iiint a(\xi, \eta) \frac{1}{r} \exp(-ikr)\cos\Theta \, d\xi \, d\eta
\]
Digital holography: recording

Phase-shifted digital holograms

0°  90°  180°  270°

Recording conditions:
- Wavelength: 782 nm
- Digital CCD camera: 10-bit, 1024 × 1024 pixels
- Pixel size of CCD: 6.24 × 6.24 µm²
- Parallel illumination and observation conditions
- Distance between object and CCD: 330 mm
- Characteristic dimension of object: 30 mm
Digital holography: reconstruction (numerical)

Reconstruction distance: 30 mm

Reconstruction distance: 45 mm
Digital holography: reconstruction (numerical)

Reconstruction distance: 125 mm

Reconstruction distance: 140 mm
Digital holography: reconstruction (numerical)

Reconstruction distance: 220 mm

Reconstruction distance: 250 mm
Digital holography: reconstruction (numerical)

Reconstruction distance: 326 mm

Reconstruction distance: 330 mm
Digital holography: reconstruction (numerical)

Reconstructed intensity: \[ I(x, y) = I_B + I_M \cos[\Delta \varphi(x, y)] \]

Intensity: \( I(x, y) \)

Phase: \( \Delta \varphi(x, y) \in [-\pi, \pi] \)
Lensless digital holography: 532 nm laser source

ADXL202 dual-axes accelerometer die

- Proof mass
- Substrate
- 4 sets, folded springs (dual axes)
- 4 sets, electrostatic combs (capacitive electrodes)

Numerical reconstruction

Numerical magnification
Lensless digital holography, tomographic measuring mode

Phase, Intensity, and Time-in-Flight analyses

Reconstruction of a digital hologram

Recovered shape with a resolution on the order of 1 nm
Full-field-of-view characterization of mode shapes

Fundamental frequency is related to the measuring accuracy of the MEMS device

Observed fundamental mode at 10.65 KHz

Continuous full-field-of-view measurements

Frequency scan: 10 kHz - 11 kHz
Testing at the wafer level: inspecting an ADXL202 wafer

Multi-scale approach

**Level-1**: measurement of individual dies

**Level-2**: stitching individual die measurements

**Level-3**: stitching patches of Level-2

**Level-4**: stitching patches of Level-3
Fiber-optic based optoelectronic holography (FOBOEH)

Single camera configuration

$K_1$ - DIR OF ILLUMINATION

$K_2$ - DIR OF OBSERVATION

$K_2 - K_1 = K$

$K$ - SENSITIVITY VECTOR

$L$ - DISPLACEMENT VECTOR

$K \cdot L = \Omega$

$\Omega$ - FRINGE-LOCUS FUNCTION

$[K] \cdot L = (\Omega)$


$L = \left[[K]^T[K]\right]^{-1}(K)^T(\Omega)$
FOBOEH
Typical experimental setup
Typical phase analysis results
Tile #8: contour depth is 1.81 ± 0.01 mm
Inspecting using an overlapped tile approach
Intermediate tiling steps: algorithm

Tile #1

Tile #2

Patch #1
Contoured section

Intermediate tiling step: 33 x 257 mm$^2$ longitudinal section
SANDIA Labs 1,000,000 rpm microengine
50 µm diameter input gear

CHSLT-NEST Laser Lab for studies of MEMS

Electrostatically driven Sandia MEMS microengine

Optoelectronic Laser Interferometry Microscope (OELIM)

Region of interest

OELIM images and displacements
2-axes MEMS accelerometer: deformation

Package in the loaded state: with excitation voltage

Interferogram

OEH results

CAD model
Characterization of micro- and nano-particles:
Holographic laser tomography for biological/materials applications
MEMS-based metrology
High-speed measurements in confined volumes

Otolaryngology applications

The Human Tympanic Membrane

Grey's Anatomy, NY, 2000

The Human Vocal Cords
Holographic otoscope systems deployed in the clinic (MEEI)

2nd Generation System

Control station

Mobile control system

Computing platform (CP)

MP-FEM Rapid Pro

Examiner screen

Laser delivery (LD) system

Otoscope head (OH)

Patient

Mechatronic otoscope positioner (MOP)
Holographic otoscope systems deployed in the clinic (MEEI)

Representative measurements: time-averaged holography

Cat Right Ear

Simple

Complex

Ordered

Chinchilla Right Ear

485 Hz – 116 dB SPL

1270 Hz – 124 dB SPL

4000 Hz – 125 dB SPL

6000 Hz – 122 dB SPL

15000 Hz – 122 dB SPL

18742 Hz – 130 dB SPL

400 Hz – 90 dB SPL

1350 Hz – 20 dB SPL

1570 Hz – 30 dB SPL

2300 Hz – 20 dB SPL

13000 Hz – 25 dB SPL

14300 Hz – 10 dB SPL
MEMS in optoelectronic metrology: SLM

Texas Instrument’s DMD

Each mirror of the DMD is individually addressable

Close-up of chip surface

Number of mirrors

480,000 to >2,000,000
MEMS in optoelectronic metrology
High-speed measurements based on holographic interferometry principles

Use of computer generated holograms
**MEMS in optoelectronic metrology**

High-speed measurements based on holographic interferometry principles

Shape measurements in '3D inspection applications'
MEMS in optoelectronic metrology
High-speed measurements based on holographic interferometry principles

CAD models for shape measurements in ‘art preservation’
Definition of models... for ‘video games’ development... CAM...
MEMS in optoelectronic metrology
High-speed measurements based on holographic interferometry principles

Mission

• Determine road characteristics
• Integrate state-of-the-art sensing
• Register data geographically
• Support of a national network
• Work with industry partners

* Courtesy of VOTERS website
MEMS in optoelectronic metrology: SOPRA
High-speed measurements based on holographic interferometry principles

- A prototype system has been developed and applied to road surface analysis
- We are currently designing a robust, low-cost, projection system that can be deployed in the field for measurements at up 60 mph driving speeds

Prototype projector on a vehicle

Typical surface road measurements
MEMS in optoelectronic metrology: art-conservation
High-speed measurements based on holographic interferometry principles

Worcester Art Museum: Sculpture titled “Funeral of a Young Maiden” Casona, South Italy. Late 4th Century BCE

Representative Measurements
Nondestructive testing: standoff detection
Hidden objects + Internal defects

Realized opto-electronic head with pulsed laser

Developed holographic system in the field
Nondestructive testing: standoff detection
Hidden objects + Internal defects

Hidden object under person’s shirt
Detected internal defect
Thank you & see you next time!

(WPI's Seal, ~1/4th of the human-air diameter)
Short list of references

- D. Gabor, “A new microscope principle,” *Nature*, 161, 777-778, 1948. (In 1971, Dr. Gabor was awarded the Nobel Prize for his invention and development of the holographic method.)
Short list of references, cont'd

Short list of references, cont'd