Multi-scale optical metrology and nondestructive testing: CAMET (Computer-Aided Optical Metrology)

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Higgins Labs, WPI
Motivation: production cycle with CAD/CAE/CAM support

.AddRange to

Original need
Need for experimental

Computer aided process planning

Computerized scheduling, requirements, shop floor control
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 capabilities

- Macroscale
- Mesoscale
- Microscale and Nanoscale
Classic Holographic Interferometry

Process consists of (1) wavefront recording on a photosensitive media, and (2) reconstruction of the recorded wavefront.

**Recording:**
- Object
- Illumination beam
- Reference beam
- Holographic plate

**Optical reconstruction:**
- Virtual object
- Observation
- Reference beam
- Holographic plate
Classic holographic interferograms

Thermo mechanical deformations in a cooling tower

Ref. Conley and Robillard, 1992

Study of vibrations in turbine blades

Ref. Elinevskii; Stetson, 1976

Art preservation

Ref. Amadesi, 1974
Digital holography: high-speed measurements

Recording

Object beam

Illumination beam

CCD camera

Digitally recorded hologram

Object

Reference beam

$\theta$

Numerical reconstruction

Reconstruction using:

- Fresnel approximation
- 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

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

✧ 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

![Light scattering diagram](image)
Lensless digital holography: long coherence length

Measuring the complex light field with intensity and phase sampling

Acquisition of phase-stepped intensity patterns via a nanopositioner (piezo):

\[ I_1(x, y) = I_B(x, y) + I_M(x, y) \cos[\Delta \phi(x, y) + \theta_1] \]
\[ I_2(x, y) = I_B(x, y) + I_M(x, y) \cos[\Delta \phi(x, y) + \theta_2] \]
\[ I_3(x, y) = I_B(x, y) + I_M(x, y) \cos[\Delta \phi(x, y) + \theta_3] \]
\[ I_4(x, y) = I_B(x, y) + I_M(x, y) \cos[\Delta \phi(x, y) + \theta_4] \]

Implemented in a pipelined video processor
Lensless digital holography: short coherence

Measuring the complex light field with intensity and phase sampling

- High-power LED’s: 470, 520, 620, 680 nm
- FWHM ≈ 25 nm
- Coherence length: ≈ 10 µm (620 nm)
- Matching of the OPLD within coherence length
- $T$ and $I$ modulation: rise and fall time of 175 nsec
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: \( a'(x, y) = \frac{1}{i\lambda} \iint a(\xi, \eta) \frac{1}{r} \exp(-ikr)\cos\Theta \, d\xi \, d\eta \)
Lensless digital holography
Principle of operation: **numerical reconstruction** of digital holograms

In-line holographic recording geometry:

Fresnel approximation integral (parabolic terms of Taylor’s expansion):

\[
U(x, y) = \int \int U(x', y') \exp\left[i k z_o + i k \frac{(x - x')^2 + (y - y')^2}{2 z_o}\right] dx' dy' = U(\zeta, \eta)
\]

Object

\( U_o(x', y') \)

CCD or CMOS

\( U(x, y) \)

Image

\( U_I(X, Y, Z) \)
Lensless digital holography
Principle of operation: numerical reconstruction of digital holograms

In-line holographic recording geometry:

Fresnel approximation integral at plane $Z$:

$$U_I(X, Y, Z) = \int \int U(x, y) \exp\left[ikZ + ik\left(\frac{(X - x)^2 + (Y - y')^2}{2Z}\right)\right] dx dy$$

Using the complex amplitude at plane $U(x, y)$:

$$U_I(X, Y, Z) = \exp\left[ik\left(z_o + Z + \frac{X^2 + Y^2}{2Z}\right)\right] \int \int \int U_o(x', y') \times$$

$$\exp\left\{ik\left[\frac{x^2 + y^2}{2}\left(\frac{1}{z_o} + \frac{1}{Z}\right) + \frac{x'^2 + y'^2}{2z_o} - x\left(\frac{x'}{z_o} + \frac{X}{Z}\right) - y\left(\frac{y'}{z_o} + \frac{Y}{Z}\right)\right]\right\} dx dy dx'dy'$$
Lensless digital holography
Principle of operation: numerical reconstruction of digital holograms

In-line holographic recording geometry: observations

Image magnification as a function of reference beam position, $z_M = -z_R$
Lensless digital holography: recording

Phase-shifted digital holograms

0°  90°  180°  270°

Recording conditions:

✧ Wavelength: 532 nm
✧ Digital CCD camera: 12-bit, 1024 x 1024 pixels
✧ Pixel size of CCD: 6.24 x 6.24 µm²
✧ Parallel illumination and observation conditions
✧ Distance between object and CCD: 80 mm
✧ Characteristic dimension of object: 2.5 mm
Lensless digital holography: 532 nm laser source

ADXL202 dual-axes accelerometer die

Numerical reconstruction

Numerical magnification

Proof mass

Substrate

4 sets, folded springs (dual axes)

4 sets, electrostatic combs (capacitive electrodes)
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

\[ K_1 - \text{DIR OF ILLUMINATION} \]
\[ K_2 - \text{DIR OF OBSERVATION} \]
\[ K_2 - K_1 = K \]
\[ K - \text{SENSITIVITY VECTOR} \]
\[ L - \text{DISPLACEMENT VECTOR} \]
\[ K \cdot L = \Omega \]
\[ \Omega - \text{FRINGE-LOCUS FUNCTION} \]

\[ [K] \cdot L = (\Omega) \]
\[ [K]^T[K] \cdot L = [K]^T(\Omega) \]

\[ L = \left[ [K]^T[K] \right]^{-1} \left( [K]^T(\Omega) \right) \]
FOBOEH for shape measurements
Typical experimental setup with a tunable wavelength source
Inspecting using an overlapping-tile approach
Typical experimental setup with a tunable wavelength source

- Precision stage range: 137 mm (0.1 mm steps)
- Tile area: 33 x 257 mm² (tile height ≈ 35 mm)

<table>
<thead>
<tr>
<th>Tile #</th>
<th>ΔT, °C</th>
<th>Contour depth, 0.01mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>1.45</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>1.45</td>
</tr>
<tr>
<td>3</td>
<td>2.5</td>
<td>2.90</td>
</tr>
<tr>
<td>4</td>
<td>2.5</td>
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<tr>
<td>5</td>
<td>5</td>
<td>1.45</td>
</tr>
<tr>
<td>6</td>
<td>9</td>
<td>0.81</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>1.81</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>1.81</td>
</tr>
</tbody>
</table>
FOBOEH: typical phase analysis results

Tile #8: contour depth is $1.81 \pm 0.01$ mm
Inspecting using an overlapping-tile approach
Intermediate tiling steps: algorithm

Tile #1

Tile #2

Patch #1
Measured longitudinal section
Intermediate tiling step: 33 x 257 mm² longitudinal section
Data imported into a CAD system (Pro/Engineer)
Design verification and quality control
Typical FOBOEH measurements
Model definition - animation of patching process
8 patches/tile, 24 tiles ≈ 47x10^6 points
MEMS in optoelectronic metrology

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

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480,000 to >2,000,000

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 interferograms
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-based endoscopy
High-speed measurements in confined volumes

Optical probe (OP) being developed for characterizing shape and deformations in confined volumes (OBJ)

$\phi$1/4” endoscope and imaging optics

Numerical aperture, NA = 0.8
MEMS-based endoscopy
High-speed measurements in confined volumes
Otolaryngology applications

The Human Tympanic Membrane

The Human Vocal Cords

Grey's Anatomy, NY, 2000
MEMS-based endoscopy: Otolaryngology applications

Preliminary *in vitro* measurements: time-averaged holography

**Cat Right Ear**

- **Simple**
  - 485 Hz – 116 dB SPL
  - 1270 Hz – 124 dB SPL
  - 4000 Hz – 124 dB SPL
  - 6000 Hz – 125 dB SPL
  - 15000 Hz – 122 dB SPL
  - 18742 Hz – 130 dB SPL

- **Complex**
  - 1270 Hz – 124 dB SPL
  - 4000 Hz – 124 dB SPL
  - 6000 Hz – 125 dB SPL
  - 15000 Hz – 122 dB SPL
  - 18742 Hz – 130 dB SPL

- **Ordered**
  - 1270 Hz – 124 dB SPL
  - 4000 Hz – 124 dB SPL
  - 6000 Hz – 125 dB SPL
  - 15000 Hz – 122 dB SPL
  - 18742 Hz – 130 dB SPL

**Chinchilla Right Ear**

- **Simple**
  - 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

- **Complex**
  - 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-based endoscopy: Otolaryngology applications
Preliminary *in vitro* measurements: time-averaged holography

Chinchilla Right Ear: 870 Hz, 20 to 50 dB SPL
(\sim A880 tone)
MEMS-based endoscopy: Otolaryngology applications
Preliminary *in vitro* measurements: stroboscopic holography

**Cat Right Ear:** ~760 nm deformation level
MEMS-based endoscopy: Otolaryngology applications
Preliminary *in vitro* measurements: stroboscopic holography

**Chinchilla Right Ear:** ~210 nm deformation level

2800 Hz – 94 dB SPL

Relative displacement (microns)
MEMS-based endoscopy: Otolaryngology applications
Definition of computational models

FEM models defined from shape measurements

FEM models to study:
- Material properties
- BC's
- Acoustic-solid interactions
- Medical research

Chinchilla Right Ear
MEMS-based endoscopy: Otolaryngology applications

Laryngoscopy with a flexible endoscope

3D endoscope (in vitro)
On-going efforts...

- 3D, real-time, metrology... medical, industrial, robotics, materials, MEMS and Nanotechnology applications....
- Validation of computational models...

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- Research sponsors...
Thank you!

(WPI’s Seal, ~1/4th of the human-air diameter)