Title: 3D Digital Holographic Interferometry: Applications in Biomedicine

Date: Aug 16, 2013  04:25 PM

URL: http://pirsa.org/13080047

Abstract: <span>Digital Holographic Interferometry (DHI) plays an important role in the evaluation of object static and dynamic displacements. The state of the art research on this technique is such that it is being used to solve problems in a wide variety of disciplines, from basic Physics to engineering and even social sciences. This invited plenary talk will deal with specific applications in some biomedical objects, even showing preliminary results using Electron Holography.</span>
Optics Express, Vol. 18, No. 6 (2010), and The Virtual Journal for Biomedical Optics Vol. 5, No. 7 (2010).

Outline of Presentation

1. Introduction
   a) Interferometry: brief history and fundamentals
   b) Theory: the basics
   c) ESPI and Digital Holographic Interferometry (DHI)

2. Results:
   a) ESPI
   b) 2D y 3D DHI
   c) Bio

3. Conclusions
Definitions

Interferometry: superposition of n E-M beams in space. The result of interference depends on the phase relations between the beams.

Interference relates to the interaction between propagating beams, while refraction, scattering and diffraction depend on the interaction between a beam and matter.
A short history of interferometry

1. XVIIc. – R. Boyle, R. Hook, observation and analysis of interference effects in a thin air layer limited by two glass plates which demonstrated the wave nature of light

2. 1690 – C. Huygens, Huyghens theorem (beginning of the wave theory of light)
   Each element of a wavefront may be regarded as the center of a secondary disturbance which gives rise to spherical wavelets and the position of the wavefront at any latter time is the envelope of such wavelets

3. 1738 T. Young experiment confirmed Huyghens’ hypothesis and gave the basis to modern theory of light coherence

4. 1818 – A. Fresnel – extension of Huyghens theorem, leading to so-called Huyghens-Fresnel principle - great importance in the diffraction theory and the basic postulate of the wave theory of light, development of stellar interferometry

1a. 1874 Lord Rayleigh used for the first time moire phenomenon
A short history of interferometry

5. 1881 – Michelson experiment (speed of light) and his further works on interferometry, stellar interferometry, high resolution interferometric spectroscopy – he is considered as the father of interferometry (Nobel prize 1907)
6. 1916 – F. Twyman modifications of Michelson interferometer
7. 1960 – invention of laser: Schawlow, Maiman, Townes, Prochorow….
8. 1948 – Gabor principles of holography
9. 1962 -Leith and Upatnieks off-axis holography and development of holographic interferometry (works of Burch, Brooks, Collier, Stetson…)
10. 1970 – Archbold, Leendertz speckle interferometry and speckle photography
11. 1982- ..Development of phase based interferogram analysis methods
11. 1995-….Rapid progress in digital holography
12. 2000-…Rapid progress in active interferometry and holography
Fundamentals of interferometry

Vector of electric field

\[ \bar{E}_i(r, t) = \bar{E}_0 \exp[i(\varphi_i(r) - \omega_i t)] \]

Resultant vector in two beam interferometry

\[ \bar{E}(r, t) = \sum_i \bar{E}_i(r, t); \quad i = 1, 2 \]

Result of two beam interference (E field intensity):

\[ I(r) \propto |\bar{E}|^2 = |\bar{E}_1 + \bar{E}_2|^2 = (\bar{E}_1 + \bar{E}_2)(\bar{E}_1 + \bar{E}_2)^* = \bar{E}_1 \bar{E}_1^* + \bar{E}_2 \bar{E}_2^* + \bar{E}_1 \bar{E}_2^* + \bar{E}_2 \bar{E}_1^* \]

\[ I(r) = I_1 + I_2 + I_{12} = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos[(\varphi_1(r) - \varphi_2(r)) - (\omega_1 t - \omega_2 t)] \]

Conditions for stationary interference field:

\[ \omega_1 = \omega_2 \]
\[ \varphi_1(r) - \varphi_2(r) = \text{const} \]

Recommended: parallel polarization of beams
Fundamentals of interferometry

Vector of electric field

\[ \mathbf{E}(\mathbf{r}, t) = \mathbf{E}_0 \exp[i(\phi(\mathbf{r}) - \omega t)] \]

Resultant vector in two beam interferometry

\[ \mathbf{E}(\mathbf{r}, t) = \sum_i \mathbf{E}_i(\mathbf{r}, t); \quad i = 1, 2 \]

Result of two beam interference (E field intensity):

\[ I(\mathbf{r}) \propto |\mathbf{E}|^2 = |\mathbf{E}_1 + \mathbf{E}_2|^2 = (\mathbf{E}_1 + \mathbf{E}_2)(\mathbf{E}_1 + \mathbf{E}_2)^* = \mathbf{E}_1 \mathbf{E}_1^* + \mathbf{E}_2 \mathbf{E}_2^* + \mathbf{E}_1 \mathbf{E}_2^* + \mathbf{E}_2 \mathbf{E}_1^* \]

\[ I(\mathbf{r}) = I_1 + I_2 + I_{12} = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos[(\phi_1(\mathbf{r}) - \phi_2(\mathbf{r})) - (\omega_1 t - \omega_2 t)] \]

Conditions for stationary interference field:

\[ \omega_1 = \omega_2 \]
\[ \phi_1(\mathbf{r}) - \phi_2(\mathbf{r}) = \text{const} \]

Recommended: parallel polarization of beams
Fundamentals of interferometry

Vector of electric field

$$\vec{E}_i(\vec{r}, t) = \vec{E}_0 \exp[i(\varphi_1(\vec{r}) - \omega_1 t)]$$

Resultant vector in two beam interferometry

$$\vec{E}(\vec{r}, t) = \sum_i \vec{E}_i(\vec{r}, t); \quad i = 1, 2$$

Result of two beam interference (E field intensity):

$$l(r) \propto |\vec{E}|^2 = \left| \vec{E}_1 + \vec{E}_2 \right|^2 = \left( \vec{E}_1 + \vec{E}_2 \right) \left( \vec{E}_1 + \vec{E}_2 \right)^* = \vec{E}_1 \vec{E}_1^* + \vec{E}_2 \vec{E}_2^* + \vec{E}_1 \vec{E}_2^* + \vec{E}_2 \vec{E}_1^*$$

$$l(\vec{r}) = l_1 + l_2 + l_{12} = l_1 + l_2 + 2 \sqrt{l_1 l_2} \cos\left[ (\varphi_1(\vec{r}) - \varphi_2(\vec{r})) - (\omega_1 t - \omega_2 t) \right]$$

Conditions for stationary interference field:

$$\omega_1 = \omega_2$$

$$\varphi_1(\vec{r}) - \varphi_2(\vec{r}) = \text{const}$$

Recommended: parallel polarization of beams
Fundamentals of interferometry

For \( \omega_1 = \omega_2 \) (usually one source applied)

\[
I(\vec{r}) = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos (\phi_1(\vec{r}) - \phi_2(\vec{r})) = a(\vec{r}) + b(\vec{r}) \cos \varphi(\vec{r}) \approx 1 + \gamma(\vec{r}) \cos \varphi(\vec{r})
\]

Where \( a(\vec{r}) \) and \( b(\vec{r}) \) are background and fringe modulation functions

\[
\gamma = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2}
\]

is the interferogram contrast

\[
\varphi(\vec{r}) = \phi_1(\vec{r}) - \phi_2(\vec{r})
\]

is the phase difference between the interfering beams
The observable physical quantity is the intensity,

\[ I = |a|^2 = (a_1 + a_2)(a_1^* + a_2^*) = \]

\[ A_1^2 + A_2^2 + A_1A_2 e^{i(\varphi_2 - \varphi_1)} + A_1A_2 e^{-i(\varphi_2 - \varphi_1)} = \]

\[ I_1 + I_2 + 2 \sqrt{I_1I_2} \cos \Delta \varphi \quad (3) \]

where \( \Delta \varphi = \varphi_1 - \varphi_2 \).

Output: interferogram
Modifications to interferograms help retrieve the imbeded phase

\[ I(x, y, t) = a(x, y) + b(x, y)\cos[2\pi [(f_{ox}x + f_{oy}y) + \nu_0(t)] + \alpha(t) + \varphi(x, y)] \]

Required controlled modifications of phase in FP:

- \( \nu_0(t) \) – introduces temporal heterodyning (running fringes)
- \( \alpha(t) \) – introduces controled phase shifts
- \( f_{ox}, f_{oy} \) – introduce spatial carrier fringes (spatial heterodyning)

However the requirement to get a high quality interferogram:

Source with spatial and temporal coherence.
Modifications to interferograms help retrieve the imbeded phase

\[ l(x, y, t) = a(x, y) + b(x, y) \cos[2\pi \left( (f_{ox} x + f_{oy} y) + \nu_0(t) \right) + \alpha(t) + \varphi(x, y)] \]

Required controlled modifications of phase in FP:

\( \nu_0(t) \) – introduces temporal heterodyning (running fringes)

\( \alpha(t) \) – introduces controlled phase shifts

\( f_{ox}, f_{oy} \) – introduce spatial carrier fringes (spatial heterodyning)

However the requirement to get a high quality interferogram:

**Source with spatial and temporal coherence.**
Available measurement methods

- Electronical
- Mechanical
- Optical
- Acoustical
- Pneumatics

- Photo-elasticity
- Optical fiber sensors
- Moiré (fringe projection)
- Speckle photography
- Shearography
- Laser vibrometer (high temporal, low spatial resolution)
- Digital holographic interferometry (high spatial, low temporal resolution)

...
Holography and speckle techniques
Holographic and speckle interferometry
Registration of optical hologram basic setup

Requirements:
1. Need to have equal optical paths of reference and object beams (within coherence length of laser)
2. During recording the phase between object and reference beams cannot change more than \( \Delta \phi_{\text{max}} < 0.2\pi \)
Basic Theoretical Considerations

Two wave addition: Object and Reference

\[ U_T = U_o + U_r \quad (1) \]

Intensity/Irradiance on the CCD sensor is proportional to

\[ I_T = U_o^* U_o + U_r^* U_r + U_o U_r^* + U_r U_o^* \quad (2) \]
Digital Holographic Interferometry (DHI)
Limitations of digital holography

The recording medium has to fulfil the Nyquist condition!
Each fringe has to be sampled by at least two pixels of CCD matrix

CCD cameras;
- resolution 1024x1534;
- Pixel size $\Delta=9\mu m$; for $4.5\mu m$
- Spatial resolution - ap. 111 lines/mm, 220l/mm
holographic materials (plates) - >3000 lines/mm.

Limitations

$$\delta = \frac{\lambda}{(2\sin(\gamma/2))}$$
Assumption: $\gamma = \sin\gamma = \tan\gamma$
For small $\gamma$

$$\gamma \leq \frac{\lambda}{(2\Delta)}$$

$$2\Delta \leq \delta \Rightarrow$$
for $\lambda=632.8\text{nm}$ and $\Delta=9\mu m$, $\gamma=3.5^\circ$

Conclusion: SMALL angular size of object (a few degrees)
i.e.
SMALL OBJECT or Object SITUATED FAR from CAMERA
Phase evaluation with 3 holograms
Tympanic Membrane

Endoscopic image of the TM

Characteristics of human TM

<table>
<thead>
<tr>
<th>特征</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Semitransparent</td>
<td></td>
</tr>
<tr>
<td>Cone shaped</td>
<td></td>
</tr>
<tr>
<td>The depth of the cone is about 1.5 mm</td>
<td></td>
</tr>
<tr>
<td>Diameter is 8-10 mm</td>
<td></td>
</tr>
<tr>
<td>Thickness varies between 55 and 140 μm</td>
<td></td>
</tr>
</tbody>
</table>
OEHO System

The inspection system consists of:

- High speed PC with dedicated software and hardware,
- Fiber optics, FS, and
- A compact optics head resembling an otoscope, OH
The TM surface height-change may be found from the difference between the reconstructed phases which are recorded before and after the small tilt of the object illuminating beam by the following equation:

\[
\Delta \varphi = 2K \sin \frac{\Delta \theta}{2} \left[ x \cos \left( \theta + \frac{\Delta \theta}{2} \right) - h(x) \sin \theta + \frac{\Delta \theta}{2} \right]
\]
3D Displacement on the TM shape
INHOMOGENEITIES DETECTION (TUMORS)

- Input sound power of approximately 661 mW, equivalent to a pressure of 2.3 x 10^5 pa.
- Laser pulse separation 14 ms, at 532 nm, 15 ns pulse width, 20 mJ/pulse, average power of 0.639 μW/cm² at the surface, and 6 m of coherence length.
- CCD with 1024 by 1280 pixels at 12 bits.
- Phantom is a semi sphere with an 8.4 cm in diameter and 4 cm height.
Unwrapped phase map without sound, gel surface free to move due to environmental disturbances

It is not possible to observe whether there is an inhomogeneity in the gel.
Without inhomogeneity and sound: resonant mode at 810 Hz.
With inhomogeneity: Malignant tumor 10 mm diameter
With 3D data the depth of the tumor may be found

Unwrapped phase maps corresponding to each illumination direction
Butterflies in-flight

Capture

Fixing

Experimental measurement
Comparison among 4 butterflies

Pterourus Multicaudata
Agraulis Vanillae Incarnata
Danaus Gillipus Cramer
Precis Evarete Felder
Comparison among 4 butterflies

- in-vivo experimentation
- High speed DHI
- Laser Verdi (Coherent V6)
- Illumination density on the insecto:
  19.6 mW/cm²
- NAC GX-1 camera
- Recordings at 4000 fps
- FOV: 90 x 100 mm
- 800 x 800 pixels
- 10 bits dynamic range
BACTERIA AND NANOPARTICLES

Determination of the surface morphology of gold-decahedra nanoparticles using an off-axis electron holography dual-lens imaging system, accepted in Micron
Research Team

- Dra. María del Socorro Hernández Montes
- Dr. Carlos Pérez López
- Dr. Manuel De la Torre Ibarra
- Dr. Jorge Mauricio Flores
- Jesus Cantu, Dr. Arturo Ponce and Prof. Miguel Jose Yacaman, UTSA