INTERFEROMETRY: CONCEPTS AND APPLICATIONS

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CIO
Mexico
INTERFEROMETRY: CONCEPTS AND APPLICATIONS

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Outline of Presentation

1. Principles of Interferometry
2. Some examples of Interferometric Systems
3. ESPI and Digital Holographic Interferometry

Recommended Literature:
1) Optical Metrology, K.J. Gasvik
2) Optics, M.V. Klein
3) Fundamentals of Optics and Modern Physics, H.D. Young
4) T. Kreis, “Handbook of Holographic Interferometry”
   WILEY-VCH Verlag GmbH & Co.KGaA, 2005
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

$$\vec{E}_i(\vec{r}, t) = \vec{E}_{i0} \exp[i(\varphi_i(\vec{r}) - \omega_i t)]$$

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):

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

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

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)

$$I(\vec{r}) = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos (\varphi_1(\vec{r}) - \varphi_2(\vec{r})) = a(\vec{r}) + b(\vec{r}) \cos \varphi(\vec{r}) \approx 1 + \gamma(\vec{r}) \cos \varphi(\vec{r})$$

Where $a(r)$ and $b(r)$ are background and fringe modulation functions

$$\gamma = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2}$$

is contrast of interferogram

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

is phase difference between the interfering beams

Graphic representation of interf. $E$ vectors
The observable physical quantity is the intensity,

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

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

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

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

Output: interferogram
Modifications of interferograms help to retrieve phase

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

Required controlled modifications of phase in FP:

\( \nu_0(t) \) – introduces temporal heterodyning (running fringes)
\( \alpha(t) \) – introduces controlled phase shifts
\( f_{0x}, f_{0y} \) – introduce spatial carrier fringes (spatial heterodyning)

*This will be discussed on Thursday*

However the requirement to get a high quality interferogram:

*Source with spatial and temporal coherence.*
Let’s use the Michelson interferometer to determine the coherence length of a laser source
The length $2x$ for which we obtain the accepted contrast of fringes is considered as the coherence length of the source.

For white light: 1 μm, single mode stabilized He-Ne: 6km
3. Useful Interferometers

Amplitude and Wavefront Division......though there are other types (only a few)

“Light waves can interfere only if they are emitted by the same source”
Interferometers

Light Source

Wavefront divider

Phase (optical path) difference

Wavefront combiner

Interference
Wavefront Division
T. Young (1801)
if \( z \gg D \), then

\[
\frac{d}{D} = \frac{x}{z} \quad \rightarrow \quad d = \frac{Dx}{z} \quad \therefore
\]

\[
\Delta \theta = \frac{2\pi Dx}{\lambda z}
\]

On substituting into eq (3)

\[
I(x) = 2I \left( 1 + \cos \left( \frac{2\pi Dx}{\lambda z} \right) \right)
\]

(8)

This equation represents a fringe pattern parallel to the y axis, with period \( \left( \frac{D}{\lambda z} \right)^{-1} \).

The Thomas Young interferometer is being used in FEL to measure its coherence!
An adaptation of Young’s interferometer is used in Michelson’ stellar interferometer to measure star diameters.

Other types of wavefront division interferometer are:

- Fresnel biprism
- Lloyd’s mirror
- Michelson stellar
Amplitude Division
Michelson Interferometer
if mirror M2 is translated a distance x, the optical path difference with respect to mirror M1 is 2x, thus

\[ \Delta \theta = \left( \frac{2\pi}{\lambda} \right) 2x \]

That gives a total intensity on the detector,

\[ I(x) = 2I \left( 1 + \cos \left( \frac{4\pi x}{\lambda} \right) \right) \] (9)
As the mirror 2 is translated a certain distance $d$, and by counting the number of maxima (bright fringe) per unit time it is possible to measure the speed of an object.

The Michelson Interferometer used with a low coherence source gives way to: low coherence reflectometry, LCR, and Optical Coherence Tomography, OCT. Study of semitransparent materials, biological tissues!
Other good examples of amplitude dividing interferometers are:

- Mach-Zehnder…QO Applications, NEW: 3 arms (as proposed by Prof. Mataloni)!
- Microchannel fabrication (Prof. Ramponi)
- Twyman-Green…optical shop testing
- Fizeau…flat mirror in FEL
Challenges for interferometry

Example: M(O)EMS Characterisation

deformation (laser interferometry)
dimensions/shape (white light interferometry)
vibration (time average laser interferometry)

and many more ...

topography (digital holography)

© Veeco
© Heliotis
© SINTEF
© Femto-ST
© Lyncée Tec
Main challenge in M(O)EMS inspection

- Wafer size increases – current diameters 6”, 8”, 12”
- Up to several thousands structures on one wafer (time issues)
- Feature size decreases – typically <10mm²
- Inspection ratio: 10⁻³ to 10⁻⁷
- 100% M(O)EMS inspection
Parallel Inspection concept

- parallel approach
- time and cost efficient
- multi-functional
- in-line inspection of:
  - shape
  - deformation
  - resonance frequencies
  - and mode shape

Micro optical LCI array

- Mirau type
Micro optical LI array

- DOE based Twyman Green type

Diagram showing the interaction of input and output with DOE1, imaging lens, DOE2, DOE3, glass wafer 1, glass wafer 2, mirror, and MEMS-wafer.
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
\[ \Delta \phi_{\text{max}} < 0.2\pi \]
Two wave addition: Object and Reference

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

Intensity/Irradiance on the CCD sensor is proportional to

\[ I_T = U_o^* U_o + U_r^* U_r + U_o U_r^* + U_r U_o^* \quad (2) \]

Apart from a scale factor, the third term is identical to the original object

Registration of digital hologram

Photographic (analog) material is replaced by CCD or CMOS matrix
Scheme for numerical reconstruction of digital hologram

Diffraction of plane wave at hologram is given by Fresnel-Kirchoff integral.

Due to small size of CCD camera versus the distance camera (hologram)-object we can use here Fresnel approximation given by:

\[
U(\xi, \eta; d) = \frac{iU_0}{\lambda d} \exp \left[ -i \frac{\pi}{\lambda d} (\xi^2 + \eta^2) \right] \int \int h(x, y) \exp \left[ -i \frac{\pi}{\lambda d} (x^2 + y^2) \right] \times \exp \left[ i \frac{2\pi}{\lambda d} (x\xi + y\eta) \right] dxdy
\]

where: \((x, y), (\xi, \eta)\) are coordinates, \(h(x, y)\) is the amplitude transmittance of hologram, \(U_0\) – is the real amplitude of reconstructing wavefront
Sampled version of the reconstructed field

The hologram function is sampled by CCD camera in MxN points with sampling periods Δx and Δy. Then the numeric representation of the previous equation is given as:

\[ U(m, n, d) = \exp\left[-i \frac{\pi}{\lambda d} (m^2 \Delta \xi^2 + n^2 \Delta \eta^2)\right] \sum_{k=0}^{M-1} \sum_{l=0}^{N-1} h(k, l) \times \exp\left[-i \frac{\pi}{\lambda d} (k^2 \Delta x^2 + l^2 \Delta y^2)\right] \exp\left[i2\pi \left(\frac{km}{M} + \frac{ln}{N}\right)\right] \]

Where \( \Delta \xi \) and \( \Delta \eta \) are the sizes of pixels in reconstructed images.

Intensity of the object field at distance d

\[ I(\xi, \eta; d) = \text{Re}^2[U(m, n, d)] + \text{Im}^2[U(m, n, d)] \]

Phase of the object field at distance d

\[ \phi(\xi, \eta; d) = \arctan \frac{\text{Im}[U(m, n; d)]}{\text{Re}[U(m, n; d)]} \]

So we can reconstruct numerically all information about an object
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: \( \gamma \approx \sin \gamma \approx \tan \gamma \)
For small \( \gamma \)

\[ \gamma \leq \frac{\lambda}{2 \Delta} \]

for \( \lambda = 632.8 \text{nm} \) and \( \Delta = 9 \mu m, \gamma \approx 3.5^\circ \)

Conclusion: SMALL angular size of object (a few degrees)
i.e.
SMALL OBJECT or Object SITUATED FAR from CAMERA
4. ESPI/TV H set-up

- cw/Pulsed Laser
- Object beam
- Reference beam
- Single mode optical fiber
- Reference beam
- IL
- Object beam
- Moving object
- CCD
- BC
- PC, and Monitor
HOLOGRAPHIC INTERFEROMETRY

- Classical
- Digital

T. Kreis, “Handbook of Holographic Interferometry” WILEY-VCH Verlag GmbH & Co.KGaA, 2005
Classical holographic interferometry

Each holographic system can be used to compare optical wavefronts formed by an object in different states (physical conditions)

Let initial state of an object is:

\[ E_{p1}(P) = A_{p1}(P) \exp[i \phi(P)] \]

After providing load (or other changes)

\[ E_{p2}(P) = A_{p2}(P) \exp[i \phi(P) + \Delta \phi(P)] \]

If the object (load) is stationary we may compare these wavefronts by:
- double exposure holographic interferometry,
- real time holographic interferometry.

If the object is vibrating we use:
- Time averaged holographic interferometry
- Stroboscopic holographic interferometry

In the case of dynamic object investigation we use impulse double exposure HI
PRINCIPLES OF DIGITAL HOLOGRAPHIC INTERFEROMETRY

Classical “track”

HOLOGRAM \( \tau_1(k,l) \)
(initial state)

ADDITION \( \tau_1(k,l) + \tau_2(k,l) \)
(double exposure)

NUMERICAL FRESNEL TRANSFORMATION
\( E(n, m, z) = \mathcal{F}\{\tau_1 + \tau_2\} \)

INTENSITY DISTRIBUTION
\( I(n, m) = |E(n, m, z)|^2 \)

INTERFERENCE PHASE DETERMINATION
\( I(n, m) \rightarrow \Delta \phi(n, m) \)

INTERFERENCE PHASE
\( \Delta \phi(n, m) \)

Digital “track”

HOLOGRAM \( \tau_2(k,l) \)
(final state)

NUMERICAL FRESNEL TRANSFORMATION
\( E_2(n, m, z) = \mathcal{F}\{\tau_2(k, l)\} \)

PHASE \( \phi_2(n, m) \)
\( = \arctan \frac{\text{Im}[E_2(n, m, z)]}{\text{Re}[E_2(n, m, z)]} \)

INTERFERENCE PHASE
\( \Delta \phi(n,m) = \phi_2(n, m) - \phi_1(n, m) \)

NUMERICAL FRESNEL TRANSFORMATION
\( E_1(n, m, z) = \mathcal{F}\{\tau_1(k, l)\} \)

PHASE \( \phi_1(n, m) \)
\( = \arctan \frac{\text{Im}[E_1(n, m, z)]}{\text{Re}[E_1(n, m, z)]} \)

\( \Delta \phi(m,n)=\begin{cases} 
\phi_2(m,n) - \phi_1(m,n) & \text{if } \phi_2(m,n) \geq \phi_1(m,n) \\
\phi_2(m,n) - \phi_1(m,n) + 2\pi & \text{if } \phi_2(m,n) < \phi_1(m,n) 
\end{cases} \)

No intermediate state: sequential monitoring by phase subtraction
X, Y, Z, Displacement Acquisition


Note: Object has to be illuminated from three different positions
Sensitivity vector

Phase difference due to surface displacement

$$\Delta \phi = \frac{2\pi}{\lambda} \mathbf{S} \cdot \mathbf{d}$$

Sensitivity vector as a function of the unity illumination and observation vectors

$$\mathbf{S} = \mathbf{s} - \mathbf{o}$$
2D measurements (an in plane and an out of plane component)

2D evaluation requires two independent sensitivity vectors

Out of plane sensitivity

\[ \mathbf{S}_1 + \mathbf{S}_2 = \mathbf{S}_z \]

From equation (7)
\[ \phi_z = \phi_2 + \phi_1 = \frac{2\pi}{\lambda} \mathbf{d} \cdot \mathbf{S}_z \] (9)

In plane sensitivity

\[ \mathbf{S}_1 - \mathbf{S}_2 = \mathbf{S}_x \]

\[ \phi_x = \phi_2 - \phi_1 = \frac{2\pi}{\lambda} \mathbf{d} \cdot \mathbf{S}_x \] (10)

Sensitivity vectors
\[
\begin{align*}
\mathbf{S}_1 &= (-\sin \alpha, 1 + \cos \alpha) \\
\mathbf{S}_2 &= (\sin \alpha, 1 + \cos \alpha)
\end{align*}
\]

From eq. (7)
\[
\begin{pmatrix}
\mathbf{d}_x \\
\mathbf{d}_z
\end{pmatrix} = \frac{\lambda}{2\pi} \begin{pmatrix}
-\sin \alpha & 1 + \cos \alpha \\
\sin \alpha & 1 + \cos \alpha
\end{pmatrix}^{-1} \begin{pmatrix}
\Delta \phi_1 \\
\Delta \phi_2
\end{pmatrix}
\] (11)
3D Sensitivity

3D evaluation requires three sensitivity vectors

Deformation components are evaluated at each point of the object’s surface

\[
\begin{pmatrix}
  d_x \\
  d_y \\
  d_z
\end{pmatrix}
= \frac{\lambda}{2\pi}
\begin{pmatrix}
  -\sin \alpha & 0 & 1 + \cos \alpha \\
  0 & -\sin \alpha & 1 + \cos \alpha \\
  \sin \alpha & 0 & 1 + \cos \alpha
\end{pmatrix}^{-1}
\begin{pmatrix}
  \Delta \phi_1 \\
  \Delta \phi_2 \\
  \Delta \phi_3
\end{pmatrix}
\] (12)
The displacement information must now be drawn on the *Object Contour (shape)*, which may be found using any of several different/complementary (optical and non-optical) techniques, viz.,

RESULTS
ESPI

- A) Underwater Sonar at 3KHz
- B) Traveling wave
- C) In-plane harmonic oscillation at 33 and 37 KHz
DHI

- A) 2D/3D set up, Dedicated software
- B) 3D component separation
- C) Tympanic membrane
- D) Tumor detection
- E) Vocal Chords
- F) Biomechanics
Experimental set up

Digital holographic interferometry
Figure No. 1: Forma y Deformaciones en Tres-Dimensiones...FMS

Forma y Deformación: Localizar Imágenes, Dar Coor., etc.

- Contorno: fforme.mat
- Pos. Camara: -50 0 1030
- Met. Cambio Pos: Solo (Holo3)
- def. T1/ampl.: a922 t0
- def. T2/phase: p922 t0

GRAFICAS

- Met. 2 lambda
- delta lambda [nm]: 0.0338
- Pos. Fuente: -188 225 570
- Pos. Fuentes il. en mm [x y z]:
  - No. 1: -1210 30 1220
  - No. 2: 600 30 970
  - No. 3: -410 640 870

Parámetros Generales

- Vista-x [mm]: 200.1
- Vista-y [mm]: 270.1
- lambda [nm]: 543.1
- Nom. Arch. en MATLAB: d
- Cen. Im. x,y: 0...1: 0.5 0.5
- Ev. Dat. cada: 8

Modo de Evaluación

- Datos T1 & T2: dT = T2 - T1 [µs]: 409.8
- Sep. Pulsos [µs]: 50
- Frecuencia [Hz]: 922
- Datos Amp, Fase: 
- Solo Datos T1

Exportar

- Nombre: uff55
- MATLAB
- ASCII
- UFF: dataset 58
- UFF: dataset 55

Instrucciones

- Cargar Imágenes
- Cargar Datos
- Evaluar

Paleta

- hsv
- hot
- gray
- prism
- cool

Elevación y Azimuth [°]: -75.45

Densidad: 1

- 3D/2D
- Forma
- Fase
- [Def. z]
- Def. z
- Cuadrícula
- [Def. y]
- Def. y
- Perspectiva
- [Def. xl]
- Def. x
Phase evaluation with 3 holograms

\[
\begin{pmatrix}
\frac{d_x}{d_y} \\
\frac{d_y}{d_z}
\end{pmatrix} = \frac{\lambda}{2\pi}
\begin{pmatrix}
S_{1x} & S_{1y} & S_{1z} \\
S_{2x} & S_{2y} & S_{2z} \\
S_{3x} & S_{3y} & S_{3z}
\end{pmatrix}^{-1}
\begin{pmatrix}
\Delta \phi_1 \\
\Delta \phi_2 \\
\Delta \phi_3
\end{pmatrix}
\]
Separation of individual displacement components

X component of displacement
Y component of displacement
Z component of displacement
### Characteristics of human TM

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</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</td>
<td>about 1.5 mm</td>
</tr>
<tr>
<td>Diameter is</td>
<td>8–10 mm</td>
</tr>
<tr>
<td>Thickness varies</td>
<td>between 55 and 140 μm</td>
</tr>
</tbody>
</table>
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
# Otoscope optics head (OH)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOV</td>
<td>$\phi = 10$ mm</td>
</tr>
<tr>
<td>Magnification</td>
<td>0.4X</td>
</tr>
<tr>
<td>DOF</td>
<td>5 mm</td>
</tr>
<tr>
<td>Contrast</td>
<td>0.82</td>
</tr>
<tr>
<td>MTF</td>
<td>52.0 lp/mm</td>
</tr>
</tbody>
</table>

### Field of View (FOV)

- 10.0 mm
- 8.5 mm
- 6.7 mm
Complex 4 kHz, 2.0 V: peak-to-peak deformation 0.660\,\mu m

Ordered 8 kHz, 1.5 V: peak-to-peak deformation 0.080\,\mu m
Rock.....noisy?
softer.....classical
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 follow equation:

$$\Delta \phi = 2K \sin \frac{\Delta \theta}{2} \left[ x \cos \left( \theta + \frac{\Delta \theta}{2} \right) - h(x) \sin \theta + \frac{\Delta \theta}{2} \right]$$
Shown: Tympanic annulus and handle of maleus
3D Displacement on the TM shape
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/cm^2 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
Malignant tumor 10 mm diameter, 3D data

Depth location with respect to the surface

[Graph showing surface displacement against surface length]
Results fitted to a straight line for calibration purposes
La amplitudes de vibración y las velocidades depende de la fonación. Así como la edad y sexo, determinan sus características fisiológicas de las cuerdas.
VOCAL CHORDS MOTION

FRINGE PATTERN

WRAPPED PHASE

2000 fps
Research on complex organical surfaces

Biomechanics, Stress calculation

Thermal deformations (transistor)

Strain/Stress

Biomechanical studies
Butterflies in-flight

Capture

Fixing

Experimental measurement
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**

- **Pterourus Multicaudata**
- **Agraulis Vanillae Incarnata**
- **Danaus Gillipus Cramer**
- **Precis Evarete Felder**
Wrapped phase maps

(a)

(b)

(c)

(d)
Unwrapped phase maps

5. Resultados Experimentales
Summary

- Interferometry is “not such an old” subject. The first ever experiment, the two slit T. Young’s interferometer, is used in today’s state of the art lasers (FEL).
- Interferometry allows the non contact more accurate measurements known today. Novel approaches are all the time on the way
- Interferometric systems are being used in many areas of Optics and Photonics, from optical shop testing to writing of Bragg gratings, to being incorporated in lab in a chip.
  Electronic Speckle Pattern Interferometry have been successfully used over the last 40 years.
- Digital Holographic Interferometry brought solutions to new challenges
ACKNOWLEDGEMENTS

MY DEEPEST APPRECIATION TO ICTP FOR HAVING INVITED ME TO CO-DIRECT THIS COURSE.......ONLY 32 YEARS AFTER I WAS ATTENDING THE “same” COURSE but as a STUDENT!!
Thank you for your kind attention