Coherent Endoscopic Metrology

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Literature

- Digital Speckle Pattern Interferometry and Related Techniques,
  P. Rastogi, Wiley, 2001
- Holographic Interferometry: Principles and Methods,
  T. Kreis, Akademie-Verlag, 1996
- Holographic Interferometry, P. Rastogi,Springer,1994
- Interferogram Analysis, D. W. Robinson, G. T. Reid, IPO Publishing, Bristol, 1993
- Laser Speckle and Related Phenomena,
  J. W. Goodman, Springer, 1975

Introduction and Motivation

Medicine and life sciences :

Requirement of new tools for detection, visualization and analysis to get more information about tissues and cells e.g. by:

- Micro-movements
- Differences in tissue elasticity
- Refractive index changes

for

- Minimal invasive (tumor) diagnostics
- Analysis of life processes

Introduction and Motivation

Medicine and life sciences :

Special requirements for medical applications / biological specimen:

- Minimal invasive
- Non contactive
- High resolution (lateral, amplitude)
- "On line" application (in vivo)

Introduction and Motivation

ESPI

Notation:

- ESPI: Electronic Speckle Pattern Interferometry
- DSPI: Digital Speckle Pattern Interferometry
- „TV-Holography"
- „electro-optic Holography"

Related: Speckle Shearing Interferometry / Digital Shearography

Introduction and Motivation

ESPI

Development

- 1971: Butters et al. first ESPI paper (qualitative fringe analysis)
- about 1979 first theoretical analysis (G. Slettemoen, K. Creath)
- 1979 Løkberg et al.: in vivo investigations of the human ear
- since 1985 phase shifting methods (K. Creath)

Introduction and Motivation

ESPI

Development

- since 1993 further development by application of CCD cameras, digital imaging processing components and improvement of phase shifting techniques
- 1993 Pedrini et al.: spatial phase shifting ESPI
- 1997 Bothe et al.: optimization of spatial phase shifting ESPI
- 1997 Løkberg et al.: Microscopic video speckle interferometry
- 2000 Schedin et al.: Shock wave detection on biological surfaces

Introduction and Motivation

ESPI

Endoscopy
- Investigation of cavities
- Compact
- Flexible

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ESPI
- Non-destructive testing
- Interferometric precision
- Video repetition rate

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Microscopy
- High lateral resolution

Applications

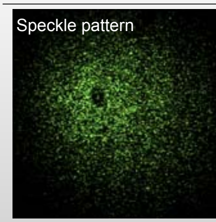
Life Sciences
- Analysis of life processes

Medicine
- Minimal invasive (tumor) diagnostics

Industry
- Non-destructive testing

ESPI

Speckle effect



Probability density $p(I)$ of the intensity distribution I

$$p(I) = \frac{1}{2\sigma^2} \cdot \exp\left(-\frac{I}{2\sigma^2}\right)$$

σ^2: mean intensity

Speckle size (in propagation direction) d'_{sp}

$$d'_{sp} \approx 8 \cdot \lambda \frac{l^2}{D_A^2}$$

Speckle size d_{sp} (lateral)

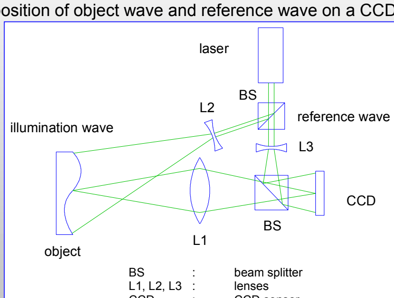
$$d_{sp} \approx 1.22 \cdot \lambda \frac{l}{D_A}$$

λ : light wavelength
l : distance to optics
D_A: aperture

ESPI

Principle

Superposition of object wave and reference wave on a CCD sensor



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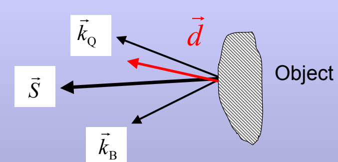
Detection of displacements



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

$$\vec{S} = \frac{\vec{k}_Q}{|\vec{k}_Q|} + \frac{\vec{k}_B}{|\vec{k}_B|}$$

$\vec{k}_Q$: Illumination direction
$\vec{k}_B$: Observation direction
λ : Light wave length

$\vec{S}$: Sensitivity vector
$\vec{d}$: Displacement vector
$\Delta\phi$: Phase difference

ESPI

Image subtraction: fast visualization

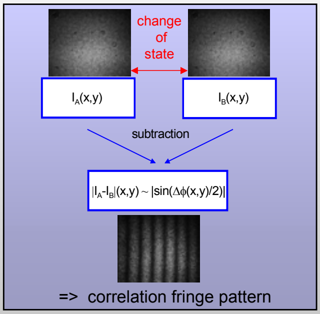


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Image subtraction

Calculation of correlation fringe patterns:

Intensity subtraction for state A and B

$$|(I_A - I_B)(x,y)| \propto |\sin[\Delta\phi(x,y)/2]|$$

with:

$$|I_A - I_B|_{\min}: \quad \Delta\phi(x,y) = (2m+1)\pi \qquad m = 0, 1, 2, 3, \ldots$$

$$|I_A - I_B|_{\max}: \quad \Delta\phi(x,y) = (2m)\pi$$

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Image subtraction

Advantages:

- Fast visualization of motions and displacements
- Simple experimental setup

Disadvantages:

- No quantitative phase evaluation without further technology
- No detection of the sign of displacements and motions

ESPI

Quantitative phase (difference) determination

Phase shifting techniques:

- Spatial heterodyne ESPI
- Temporal phase shifting ESPI
- Spatial phase shifting ESPI

ESPI

Spatial heterodyne ESPI

- Further development of the image subtraction method
- Additional tilt of the reference wave or of the object wave between two recordings
- Correlation fringes of the object displacement are superposed e.g. with additional parallel carrier fringes
- Evaluation of the phase difference distribution by Fast Fourier transformation

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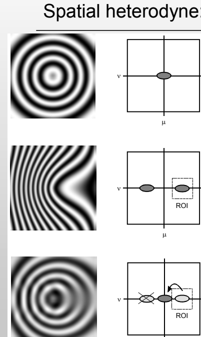
Spatial heterodyne: centrally loaded plate



without carrier frequency

$$c(x,y) = \mathrm{FT}\{|I_A - I_B|(x,y)\}$$

FT: Fourier Transformation

with carrier frequency f

$$c(x,y,f) = \mathrm{FT}\{|I_A - I_B|(x,y,f)\}$$

==> $$\Delta\phi(x,y) = \arctan\left[\frac{\Im[(I_A - I_B)(x,y)]}{\Re[(I_A - I_B)(x,y)]}\right]$$

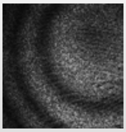
$$c(x,y,f) \Rightarrow c'(x,y)$$

$$(I_A - I_B)(x,y) = \mathrm{FT}^{-1}\{c'(x,y)\}$$

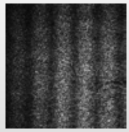
ESPI

Spatial heterodyne: centrally loaded plate

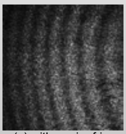
example: central loaded plate



(a) Correlation fringe pattern: Central loaded plate



(b) Carrier fringes



(c) Image (a) with carrier fringes from (b)

(d) Phase difference of (a)

ESPI

Spatial heterodyne ESPI

Advantages:
- Fast visualization and detection of motions and displacements with correct sign
- Investigations under “instable conditions” possible (one recording per object state)

Disadvantages:
- Displacements and motions not directly visible
- Movable parts (e. g. piezo translators) for phase shifting and synchronization necessary
- Reduced lateral resolution

TPS ESPI

(Difference) Phase determination

$$I_n(x,y,t_n) = I_0(x,y)[1+\gamma(x,y)\cdot\cos(\phi_O(x,y)+\alpha_n(t_n))]$$

e. g.

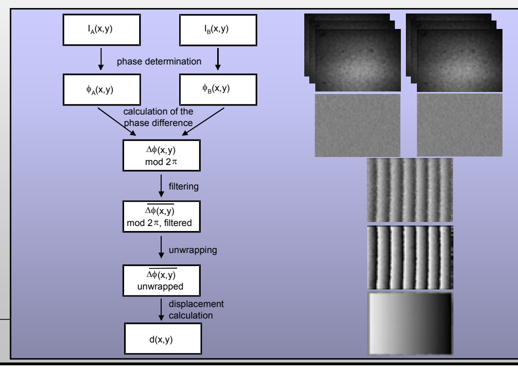
$$\phi_O(x,y) = \arctan\left(\frac{I_4(x,y)-I_2(x,y)}{I_1(x,y)-I_3(x,y)}\right) \mod 2\pi$$

reference wave phase $\alpha_n(t_n)$

$\alpha_1(t_1),\ \alpha_2(t_2),\ \alpha_3(t_3),\ \alpha_4(t_4)$ = 0°, 90°, 180°, 270°

TPS ESPI

Phase difference evaluation by temporal phase shifting



TPS ESPI

Temporal phase shifting (TPS) ESPI

Advantages:
- Common phase shifting method
- Detection of motions and displacements with correct sign
- No reduction of lateral resolution

Disadvantages:
- Movable parts (e. g. piezo translators) or liquid crystal displays necessary for phase shifting
- Investigations under “instable conditions” critical (several recordings per object state)

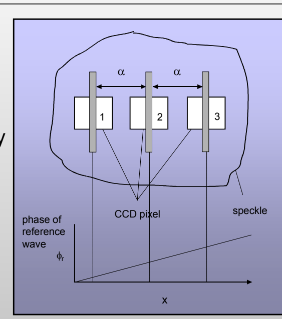
==> critical for investigations on biological specimen

SPS ESPI

Spatial phase shifting (SPS)

Superposition of the speckle pattern with an additional constant spatial carrier fringe frequency

Comparison of the recorded intensity values of neighboring CCD pixels



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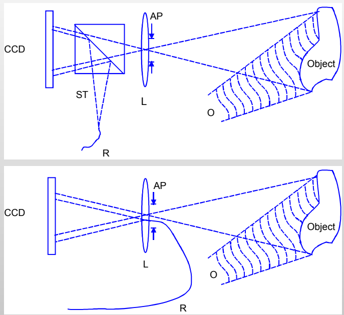
Spatial phase shifting (SPS)

Realization of a nearly constant phase gradient between object wave and reference wave



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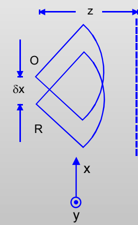
Phase determination

Spatial carrier frequency ν_0 and phase gradient β between object wave ϕ_O and reference wave ϕ_R :



$$\psi(x,y,z)=\phi_R(x,y,z)-\phi_O(x,y,z)$$

$$\psi(x,y=0,z)=\left(\sqrt{(x+\delta x)^2+z^2}-\sqrt{x^2+z^2}\right)\cdot\frac{2\pi}{\lambda}$$

$$\beta(x)=\frac{\partial\psi}{\partial x}=\left(\frac{\delta x+x}{\sqrt{(x+\delta x)^2+z^2}}-\frac{x}{\sqrt{x^2+z^2}}\right)\cdot\frac{2\pi}{\lambda}$$

$\beta(x)\approx\beta\approx\text{const},\quad \alpha_k=k\beta$

$\beta=2\pi\nu_0$

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Phase difference evaluation

Intensity distribution on the CCD sensor:

$$I(x_m,y_n)=I_0(x_m,y_n)\times\left[1+\gamma(x_m,y_n)\operatorname{sinc}\left(\frac{\Phi}{2}\right)\cos(\phi_O(x_m,y_n)+k\beta+C)\right]$$

Phase reconstruction e. g. by variable 3-step-method:

$$\phi_{O,k}(x,y)+k\beta+C=\arctan\left(\frac{1-\cos\beta}{\sin\beta}\,\frac{I_{k-1}-I_{k+1}}{2I_k-I_{k-1}-I_{k+1}}\right)\quad \text{modulo}\quad 2\pi$$

here: $\beta\approx$ const

Phase difference: $\Delta\phi_k=\phi_{O,k}-\phi'_{O,k}$ (modulo 2π)

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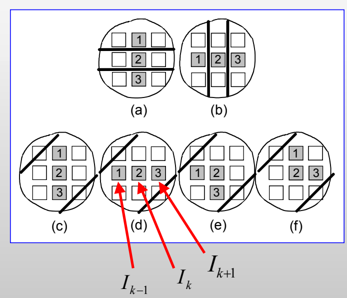
Phase determination

Superposition of the speckle pattern with an additional spatially constant carrier fringe frequency

Comparison of the recorded intensity values of neighboring CCD pixels



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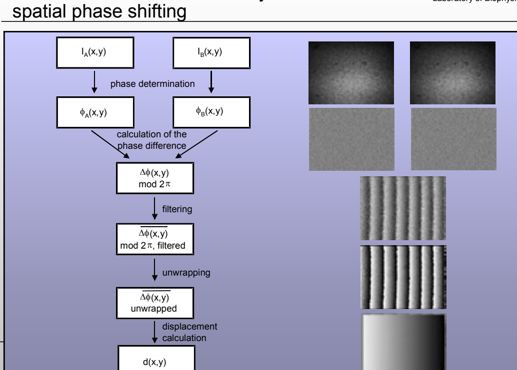
Phase difference evaluation by spatial phase shifting



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Spatial phase shifting ESPI

Advantages:

- Fast visualization and sign correct detection of motions and displacements
- Investigations under “instable conditions” possible (one recording per object state)
- No movable parts (e. g. piezo translators) for phase shifting necessary

Disadvantages:

- Reduced lateral resolution

==> suitable for investigations on biological specimen

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Adjustment of the spatial carrier frequency $\nu_0 = (\nu_{x0}, \nu_{y0})$ by digital holography

Digital Fourier transform (FT) of the intensity distribution of superposed object wave and reference wave:

$$I(x,y) = |E_O(x,y) + E_R(x,y)|^2$$

Digital holographic reconstruction of the aperture of the optical imaging system

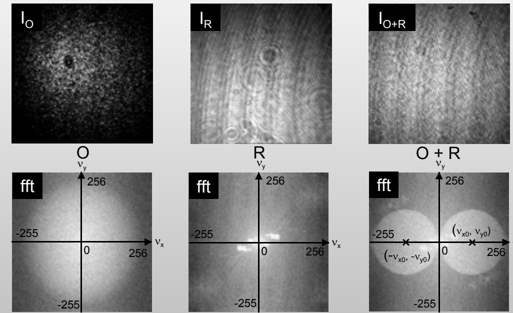
$$\mathrm{FT}\{I\} = |E_R|^2 \delta(\nu_x, \nu_y) + \mathrm{FT}\{|E_O|^2\} + |E_R| \mathbf{E}_O(\nu_x - \nu_{x0}, \nu_y - \nu_{y0}) + |E_R| \mathbf{E}_O^*(\nu_x + \nu_{x0}, \nu_y + \nu_{y0})$$

==> Determination of the phase gradient β:

$$\beta = (\beta_x, \beta_y) = 2\pi(\nu_{x0}, \nu_{y0})$$

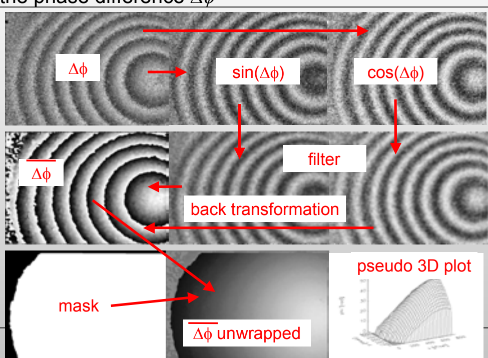
SPS ESPI

Adjustment of the spatial carrier frequency $\nu_0 = (\nu_{x0}, \nu_{y0})$ by digital holography



ESPI

Further evaluation of the phase difference $\Delta\phi$



SPS ESPI

Further evaluation of the phase difference $\Delta\phi$

Intensity Distribution on the CCD Sensor

$$I(x,y) = I_0(x,y)\left\{1 + \gamma_0(x,y)\,\mathrm{sinc}\left(\frac{\delta}{2}\right)\cos[\phi_O(x,y) + \beta]\right\} = I_0(x,y)\{1 + \gamma(x,y)\cos[\phi_O(x,y) + \beta]\}$$

with

$$a_0(x,y) = I_0(x,y)$$
$$a_1(x,y) = I_0(x,y)\gamma(x,y)\cos[\phi_O(x,y)]$$
$$a_2(x,y) = I_0(x,y)\gamma(x,y)\sin[\phi_O(x,y)]$$

$\phi(x,y)$ and $\gamma(x,y)$ are calculated from adjoining CCD pixels.

$$\phi_O(x,y) = \tan^{-1}\left[\frac{-a_2(x,y)}{a_1(x,y)}\right] \qquad \gamma(x,y) = \frac{\sqrt{a_1(x,y)^2 + a_2(x,y)^2}}{a_0(x,y)}$$

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Determination of the modulation γ

m-step-algorithm ($\beta = 2\pi/(N\cdot\text{pixel})$)

$$\phi = \tan^{-1}\left[\frac{\sum_{n=1}^{N} I_n(x,y)\sin\left(\frac{2\pi n}{N}\right)}{\sum_{n=1}^{N} I_n(x,y)\cos\left(\frac{2\pi n}{N}\right)}\right] \qquad \gamma = \frac{\sqrt{\left(\sum_{n=1}^{N} I_n(x,y)\sin\left(\frac{2\pi n}{N}\right)\right)^2 + \left(\sum_{n=1}^{N} I_n(x,y)\cos\left(\frac{2\pi n}{N}\right)\right)^2}}{2I_0}$$

5-step-algorithm (β = 90°/pixel)

$$\phi = \tan^{-1}\left[\frac{2(I_2 - I_4)}{-I_1 + 2I_3 - I_5}\right] \qquad \gamma = \frac{\sqrt{[2(I_2 - I_4)]^2 + (-I_5 + 2I_3 - I_1)^2}}{4I_0}$$

4-step- algorithm (β = 90°/pixel)

$$\phi = \tan^{-1}\left[\frac{I_4 - I_2}{I_1 - I_3}\right] \qquad \gamma = \frac{\sqrt{(I_4 - I_2)^2 + (I_1 - I_3)^2}}{2I_0}$$

3-step- algorithm (β = variable, known)

$$\phi = \tan^{-1}\left[\left(\frac{1 - \cos\beta}{\sin\beta}\right)\frac{I_1 - I_3}{2I_2 - I_1 - I_3}\right] \qquad \gamma = \frac{\sqrt{[(1 - \cos\beta)(I_1 - I_3)]^2 + [\sin\beta(2I_2 - I_1 - I_3)]^2}}{2I_0 \sin\beta(1 - \cos\beta)}$$

SPS ESPI

Determination of the modulation γ

3-step-algorithm (β = variable, known)

phase of object wave

$$\phi = \tan^{-1}\left[\left(\frac{1 - \cos\beta}{\sin\beta}\right)\frac{I_1 - I_3}{2I_2 - I_1 - I_3}\right]$$

modulation

$$\gamma = \frac{\sqrt{[(1 - \cos\beta)(I_1 - I_3)]^2 + [\sin\beta(2I_2 - I_1 - I_3)]^2}}{2I_0 \sin\beta(1 - \cos\beta)}$$

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Further evaluation of
the phase difference $\Delta\phi$

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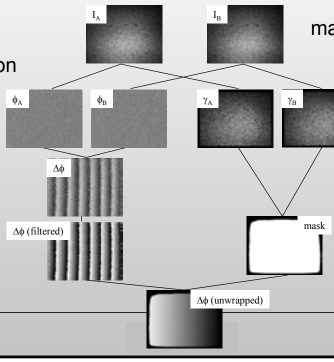
Phase difference determination

mask generation



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Further evaluation of
the phase difference $\Delta\phi$

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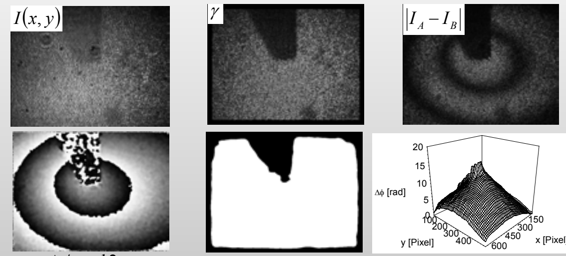
Example: technical membrane



$\Delta\phi \bmod 2\pi$ filtered | mask | $\Delta\phi$ unwrapped