Summary

- Full-field measurements: A general view

- The important elements
  - Sensor
  - Physical principles
  - Encoding
  - Algorithm (decoding)

- A few applications

- Conclusion
Full-field measurements

- **General principle**
  - Four important ‘boxes’

Specimen - Sensor - Imaging system - Algorithm - ‘images’ - Encoding - Mechanical quantity - Physical principle

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Sensors – 1/5

- **CCD/CMOS**
  - Charge-Coupled Device (1969)
  - Complementary Metal-Oxyde Semi-conductor
  - Principle: photons hitting the sensor generate electrons by photoelectric effect

[CCD and CMOS images]

source: wikipedia
- High speed cameras

Sensors – 3/5

- Common features
  - Discrete information (from $10^5$ to $10^7$ pixels)
  - Electronic noise
Sensors – 4/5

- Noise

Mean = 145 grey levels
Std = 637 grey levels

Noise: 637/65520
0.97% of dynamic range
- Noise scales up with grey level
  - Take many images and work out mean and standard deviation

![Graph showing Noise Evolution with 1.5% and 0.2% of dynamic range indicated]
Physical principles – 1/5

- Reflected light
  - Different types of light/solid interactions

Incident light

Absorbed

Reflected light

Transmitted
Light / solid interaction - 1/3

- **Diffusive reflection**
  - Light scattered in all space directions when seeing change of index
  - Also known as ‘scattering’
Specular reflection
- Light scattered in a particular space direction
**Diffractive reflection**

- Light scattered in particular space directions

**Order**
- Order -2
- Order -1
- Order 0
- Order 1
- Order 2

**Diffraction grating** (pitch close to light wavelength)
Physical principles – 2/5

- Intensity or phase of reflected light
  - Diffusive, grating or specular reflection
  - Random or periodical pattern
  - Sensor: CCD/CMOS
  - Encoded information: displacements (in-plane, out-of-plane), displacement gradients

- Interaction of an electron beam with a conductive material
  - Scanning Electron Microscope (complex image forming, image distortion, beam drift)
  - Transmission electron Microscope (TEM)
Physical principles – 3/5

- Mechanical probing for surface profiles
  - Atomic Force Microscope (AFM)
  - Mechanical profilometers

- Short coherence of white light
  - White light interferometer (surface profiles)

- Nuclear Magnetic Resonance
  - Contrast in water contents
  - Many variants of MRI
  - Magnetic Resonance Elastography: direct encoding of displacements
Physical principles – 4/5

- X-ray absorption
  - X-ray photography
  - X-ray tomography

- Bone, foam, cast iron, syntactic foams...

Reconstruction algorithm
Physical principles – 5/5

- Contrast in light index
  - Optical Coherence Tomography (OCT)

Eye cornea


Silicone gel seeded with copper particles
Encoding – 1/6

- Surface or internal pattern deforms as material
  - Easiest phenomenon, intuitive
  - Encoded information: displacements
Encoding – 2/6

- Reflected image deforms
  - Specular reflection
  - Encoded information: slope

\[ d = 2h \cdot da \]
Encoding – 3/6

- Interferences of light waves
  - Diffusive or diffractive reflection
  - Encoded information: displacements

\[
E_x^1 = E_x^0 \cos\left(\frac{2\pi}{\lambda} z - \omega t\right) \quad E_x^2 = E_x^0 \cos\left(\frac{2\pi}{\lambda} (z + \delta z) - \omega t\right)
\]

\[
(E_x^1(t) + E_x^2(t))^2 = (E_x^0)^2 \left(1 + \cos\frac{2\pi}{\lambda}\delta z\right)
\]

Fringe pattern
Notion of sensitivity vector

\[ \Delta \phi_1 = -\frac{2\pi}{\lambda} \overrightarrow{k_e} \cdot \overrightarrow{u} \]

\[ \Delta \phi_2 = \frac{2\pi}{\lambda} \overrightarrow{k_i} \cdot \overrightarrow{u} \]

\[ \Delta \phi_t = -\frac{2\pi}{\lambda} (\overrightarrow{k_e} - \overrightarrow{k_i}) \cdot \overrightarrow{u} \]

Sensitivity vector \( \overrightarrow{g} = \overrightarrow{k_e} - \overrightarrow{k_i} \)
Encoding – 5/6

- Out-of-plane measurements

Sensitivity: one fringe \((2\pi \text{ phase})\) corresponds to

\[
\frac{\lambda}{2 \cos(\alpha / 2)}
\]

\(\alpha = 0\)
\(\lambda = 500 \text{ nm}\)
\(\rightarrow 250 \text{ nm}\)
In-plane measurements

Sensitivity: one fringe (2π phase) corresponds to

\[ \frac{\lambda}{2 \sin \alpha} \]
Algorithms – 1/4

- **Pattern correlation (‘image registration’)**
  - Conservation of optical flow (grey level values conserved through deformation)
  - Pixel scale: lack of uniqueness → subset
  - Parameterize \( u \) and \( v \): shape functions
  - Matching criterion
  - Interpolation (subpixel accuracy)

\[
g(x,y) \quad \quad g'(x+u,y+v)
\]

Minimize \((g-g')^2\)
 Algorithms – 2/4

- **Pattern correlation**
  - Extends to stereo-vision: 2 cameras with different view (Stereo-DIC)
  - Extends to volume images: DVC
  - Very general: works on random and not so random patterns
  - No a priori knowledge: limits performances
Algorithms – 3/4

- Phase detection
  - Temporal phase shifting

\[ I = I_0 (1 + \gamma \cos \varphi(x)) \]

Mirror with piezoelectric actuator

\[ I = I_0 (1 + \gamma \cos[\varphi(x) + \Delta \varphi]) \]
Phase detection for regular ‘grids’

- Spatial phase shifting

\[ I(x) = I_0(0) \left[ 1 + \gamma(0) \sin \left( \frac{2\pi x}{p} + \phi(0) \right) \right] \]

\[ \phi = \text{Arc tan} \left( \frac{I_{\text{pix}1} - I_{\text{pix}3}}{I_{\text{pix}4} - I_{\text{pix}2}} \right) \]
An important remark

- Measurement acts as a spatial filter
- Smallest sampling size: pixel
  - Temporal phase shifting
- Effective sampling size
  - Subset (correlation), typically 25 x 25
  - Number of sampling pixels (spatial phase shifting), typically 5 x 5
- Noise: random error
- Sampling: systematic error
A few examples – 1/12

- Speckle interferometry (also called ‘ESPI’)
  - Interferences, diffusive reflection, temporal phase shifting

- Tensile test on a magnesium friction stir weld
A few examples – 2/12

- Longitudinal strain component
A few examples – 3/12

- Speckle interferometry
  - By the way, speckles are not necessary, they are a nuisance (and source of decorrelation)

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A few examples – 4/12

- Moiré interferometry
  - Interferences, grating reflection, temporal phase shifting

Wu et al, CRAS, 2001
Hole diameter: 2 mm

Speckle interferometry
A few examples – 5/12

- Grid method
  - Intensity, diffusive reflection, spatial phase shifting

Projectile: steel, 30 mm diameter, 40 mm long, 30 m.s⁻¹

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A few examples – 6/12

- **Camera**
  
  SHIMADZU HPV-X  
  Inter-frame time: 0.2 $\mu$s  
  Spatial resolution: 400 by 250  
  Recorded images: 128

- **Grid**
  
  - Grid pitch: 0.6 mm  
  - 5 sampling pixels per period

- **Material**
  
  - Carbon/epoxy QI $[0/\pm 45/90]_s$
A few examples – 7/12

\[ a_x \text{ in } m/s^{-2} \text{ at } 2.6 \mu s \]

\[ \varepsilon_x \text{ at } 2.6 \mu s \]

\[ x \times 10^6 \]

\[ x \times 10^{-3} \]

\[ |\omega| \times 10^{-3} \]

\[ \text{time: } \mu s \]
A few examples – 8/12

- Deflectometry
  - Intensity, specular reflection, spatial phase shifting


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A few examples – 9/12

- Carbon/epoxy plate excited at 99.8 kHz

<table>
<thead>
<tr>
<th>deflection (nm)</th>
<th>slope x (mm/km)</th>
<th>slope y (mm/km)</th>
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</table>

<table>
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<tr>
<th>strain x (µm/m)</th>
<th>strain y (µm/m)</th>
<th>strain s (µm/m)</th>
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</thead>
</table>
A few examples – 10/12

- PMMA plate excited at 100 kHz
A few examples – 11/12

- Grid method
  - Surface profile (WLI), spatial phase shifting
  - Grid pitch: 5.3 µm (interferometric lithography)
  - Field of view: about 275 by 200 mm²
A few examples – 12/12

- Result (mild steel, 300 x 200 \( \mu m^2 \))

Conclusion – 1/2

- Overview of main techniques
  - Image pixel size of 10 µm
  - 1000 by 1000 CCD camera

<table>
<thead>
<tr>
<th></th>
<th>DIC</th>
<th>GM</th>
<th>SI</th>
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<tbody>
<tr>
<td>Spatial resolution</td>
<td>32</td>
<td>9</td>
<td>10^6</td>
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<tr>
<td>in pixel indep. data points</td>
<td>960</td>
<td>12100</td>
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<td>Displacement resolution</td>
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<tr>
<td>in pixel in µm</td>
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<td>0.01</td>
<td>0.001</td>
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<tr>
<td></td>
<td>0.1</td>
<td>0.1</td>
<td>0.01</td>
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</tbody>
</table>
Conclusion – 2/2

- Overview of possibilities

- Important issue: uncertainty quantification
  - Need for more metrological concepts
  - Critical: low pass filtering effect of DIC

- DIC is not a synonym of FFM (‘toolbox’)

- Need for more training

- Future: integration with data processing
  - MatchID platform, www.matchIDmbc.com
More?

- 5 days DIC course: diccourse.matchid.org
  - 11-15 January 2016 in Ghent, Belgium

  Dr Philip Reu
  Sandia National Laboratories, USA

  Prof. Pascal Lava
  KU Leuven, Belgium

  Yours truly

- BSSM Experimental Mechanics workshop
  - 11 – 15 April 2016 at the University of Southampton, www.bssm.org (Prof. J. Barton)