WORCESTER POLYTECHNIC INSTITUTE
MECHANICAL ENGINEERING DEPARTMENT

Optical Metrology and NDT
ME-593L, C'2018

Introduction: Fringe Skeletonization
February 2018

Quantitative analysis

Fringe skeletonization

- Recording of interferograms
- Identification of boundary area (AOI)
- Preprocessing, e.g., filtering
- Identification of fringe centers
- Numbering of interference fringes: fringe ordering
- Reconstruction of phase using interpolation
    - Review reference papers (list is on next page)

Quantitative analysis

Fringe skeletonization

Reference papers:

- J. Novak, "Techniques for automatic identification and numbering of interference fringes using MATLAB."
- T. Merz, D. Paulus, and H. Niemann, "Line segmentation for interferograms of continuously deforming objects."
- L. Z. Cai, Q. Liu, and X. L. Yang, "A simple method of contrast enhancement and extremum extraction for interference fringes."
- J. Budzinski, "SNOP: a method for skeletonization of a fringe pattern along the fringe direction."

Fringe skeletonization

Recording of interferograms

- Classic interferometry
  - Michelson
  - Mach-Zehnder
  - Sagnac
- Holographic interferometry
- Digital holographic interferometry
- Speckle pattern interferometry
- White-light interferometry

Fringe skeletonization

Identification of boundary area

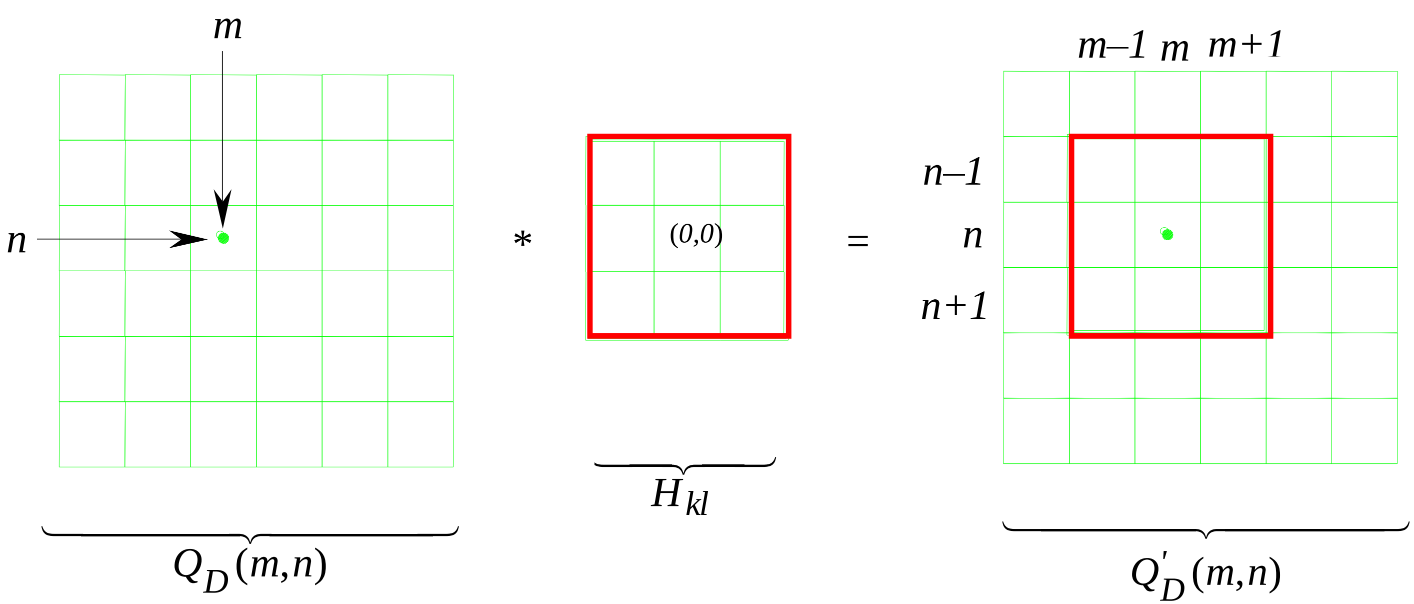
- Identification of area of interest (AOI)
  - Area of operation
  - Selection of convolution Kernel
  - Minimization of power leakage

Fringe skeletonization

Pre-processing, e.g., filtering: convolution

Application of digital spatial convolution to the pixel located at the (m,n) image plane position

Image convolution: $\boxed{Q_D(m,n) * H_{kl} = Q'_D(m,n)}$



Original image

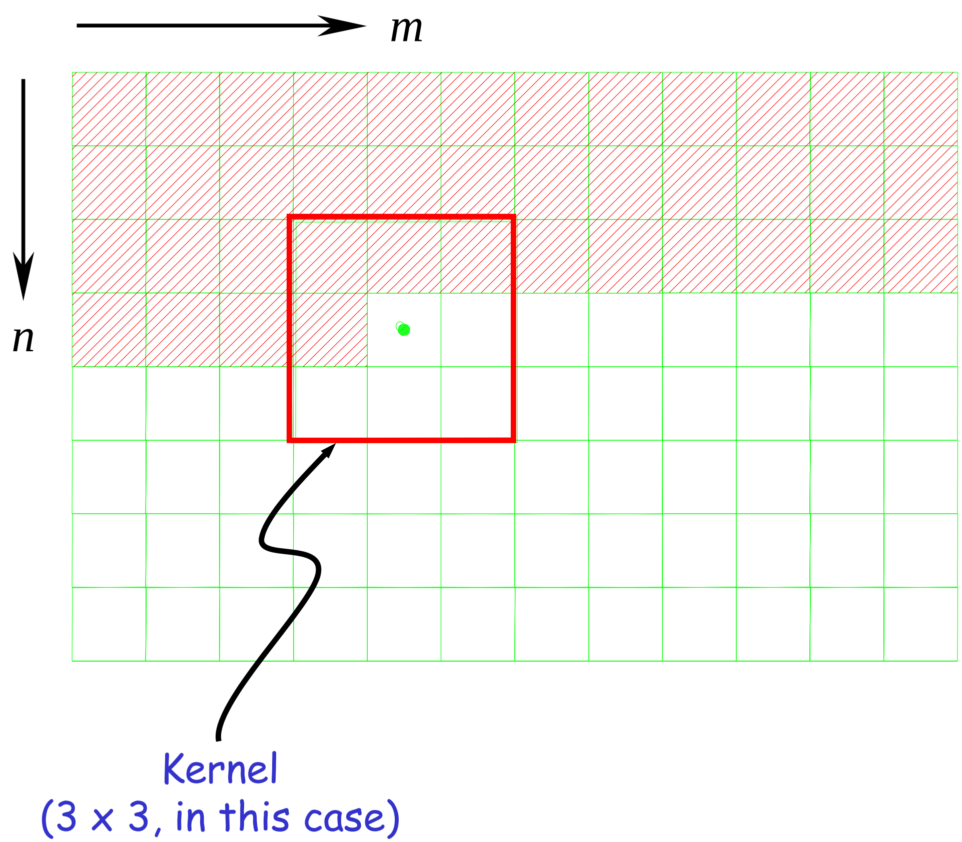
Kernel

Convolved image

Fringe skeletonization

Pre-processing, e.g., filtering: convolution

Digital spatial convolution by scanning the convolution kernel line by line over the entire image plane



Fringe skeletonization

Pre-processing, e.g., filtering: convolution

Low-pass filtering

Image convolution: $$Q_D^{'}(m,n) = \frac{1}{(2r+1)\cdot(2r+1)} \sum_{k=-r}^{r} \sum_{l=-r}^{r} Q_D(m+k, n+l)$$

Weighting factors: $$H_{kl} = \frac{1}{(2r+1)\cdot(2r+1)}$$

Fringe skeletonization

Pre-processing, e.g., filtering: convolution

Median filtering

Digital spatial convolution to median filtering the pixel value located at the (m,n) image plane position

Original image (m across, n down)

100	135	41	53	44	132
86	16	12	133	20	163
12	74	33	14	82	244
255	31	70	25	98	64
7	23	3	32	126	86

(a)

Convolved image (m across, n down)

100	135	41	53	44	132
86	16	12	133	20	163
12	4	31	14	82	244
255	31	70	25	98	64
7	23	3	32	126	86

(b)

12	14	16	25	31	33	70	74	133

Sorted list

Kernel
(3 x 3, in this case)

Fringe skeletonization

Pre-processing, e.g., filtering: convolution

Fourier filtering

Fourier transformation: $Q_D(f_u, f_v) = \wp\{Q_D(m,n)\}$

Convolution in the frequency domain: $Q_D^T(f_u, f_v) = Q_D(f_u, f_v) \cdot W_f(f_u, f_v)$

$W_f(f_u, f_v)$ is the weighting function

Inverse Fourier transformation: $Q_D^{'}(m,n) = \wp^{-1}\{Q_D^T(f_u, f_v)\}$

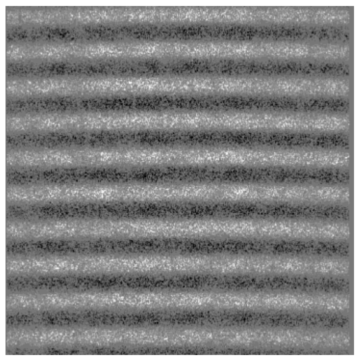
Fringe skeletonization

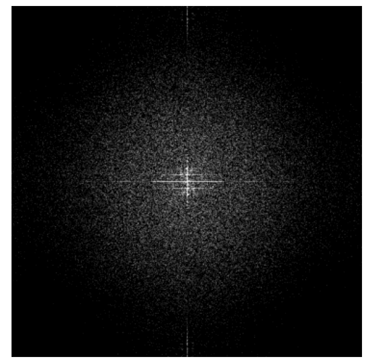
Pre-processing, e.g., filtering: convolution

Fourier filtering

Fourier transformation: $Q_D(f_u, f_v) = \mathcal{F}\{Q_D(m,n)\}$

Original interferogram





Original interferogram: frequency domain

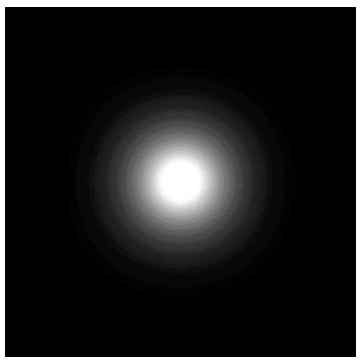
Fringe skeletonization

Pre-processing, e.g., filtering: convolution

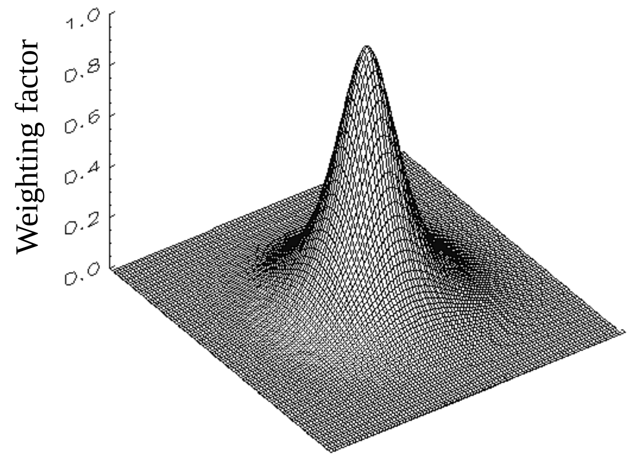
Fourier filtering

$W_f(f_u, f_v)$, weighting function: Gaussian function

2D representation



3D representation



Fringe skeletonization

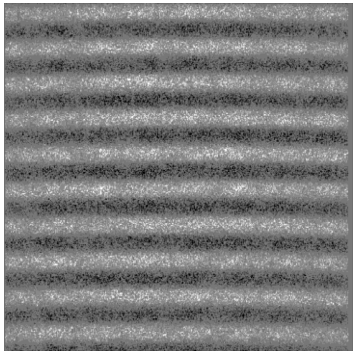
Pre-processing, e.g., filtering: convolution

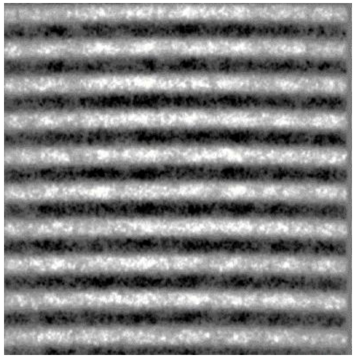
Fourier filtering

Convolution in the frequency domain: $Q_D^T(f_u, f_v) = Q_D(f_u, f_v) \cdot W_f(f_u, f_v)$

Inverse Fourier transformation: $Q_D'(m,n) = \wp^{-1}\{Q_D^T(f_u, f_v)\}$

Original interferogram





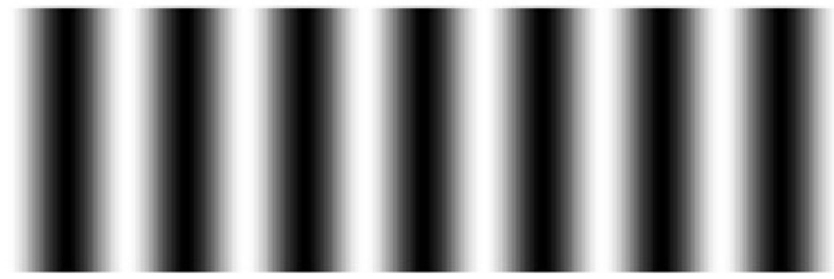
Filtered interferogram

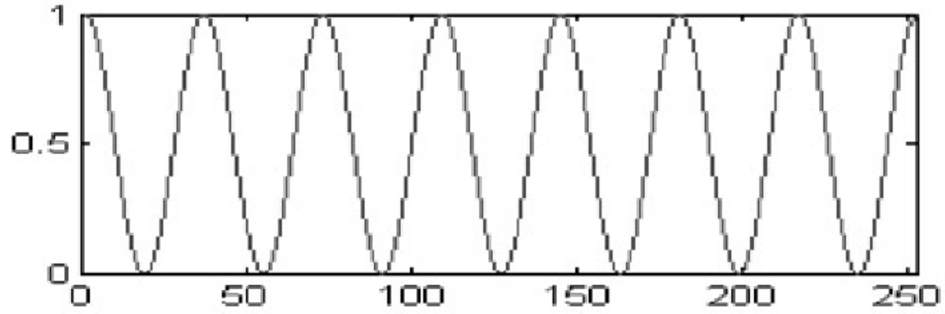
Fringe skeletonization

Pre-processing: thinning

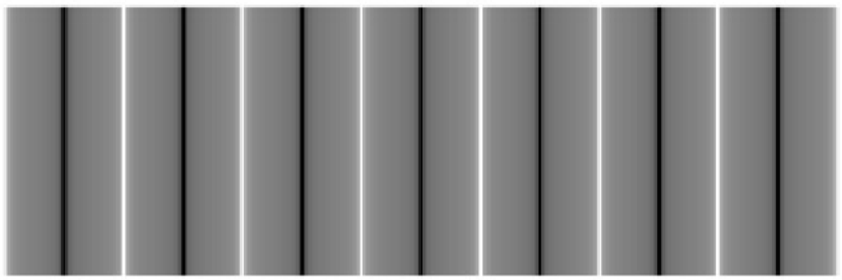
Multiple algorithms exist, e.g., contrast enhancement, edge detection, etc.

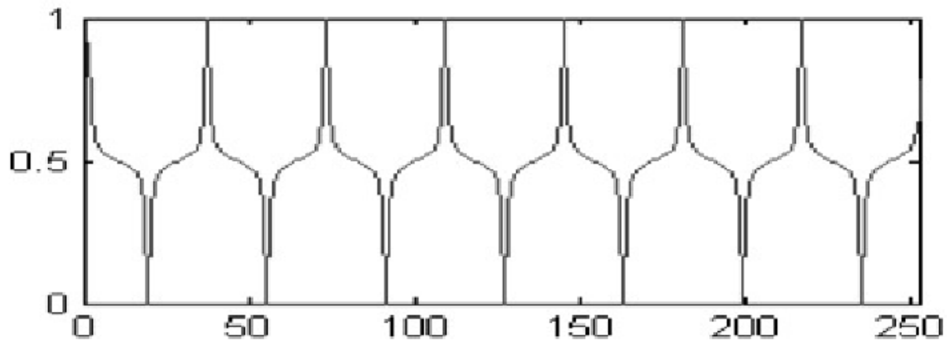
Original interferogram





Thinned fringes: contrast enhancement

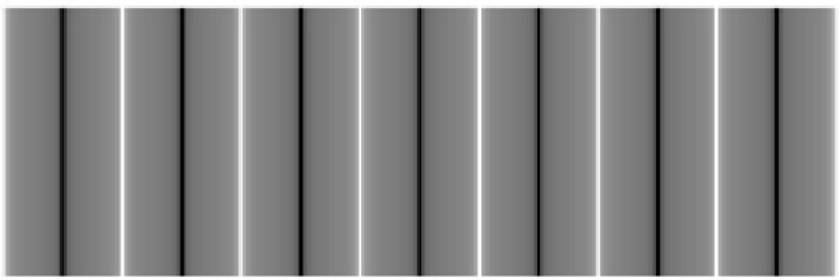


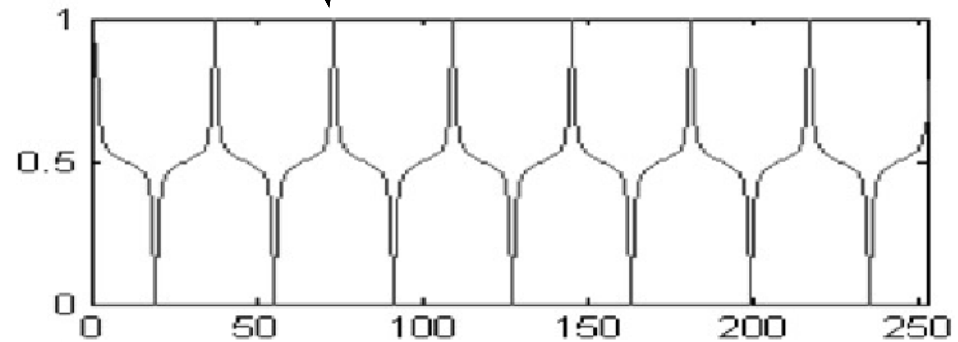


Fringe skeletonization

Identification of fringe centers

Fringe centers



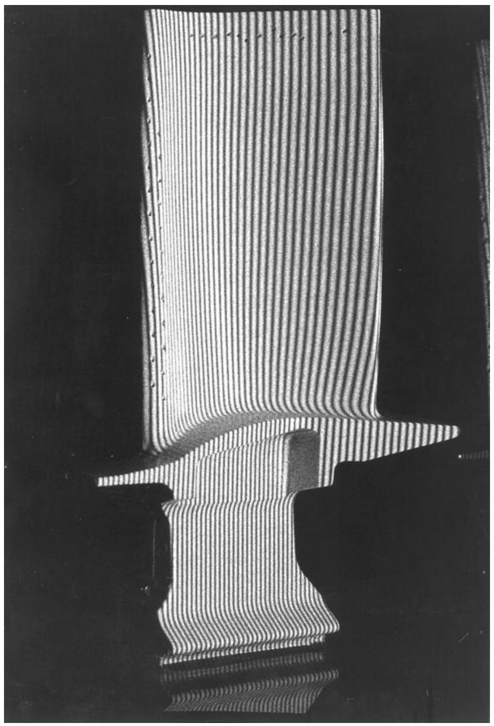


Thinned fringes: contrast enhancement

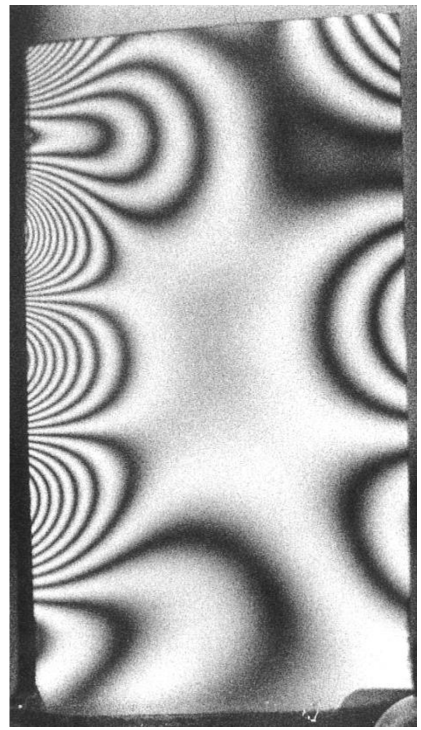
Semi-quantitative analysis

1 fringe is ≈ $2\pi/\lambda$: fringe ordering and counting

Interferogram of a turbine blade: contouring



Interferogram of a turbine blade: vibrations



Fringe-locus function (fringe localization):

$$\Omega(x, y, z) = \boldsymbol{K} \bullet \boldsymbol{L}$$

$$\Omega(x, y, z) = 2\pi n$$

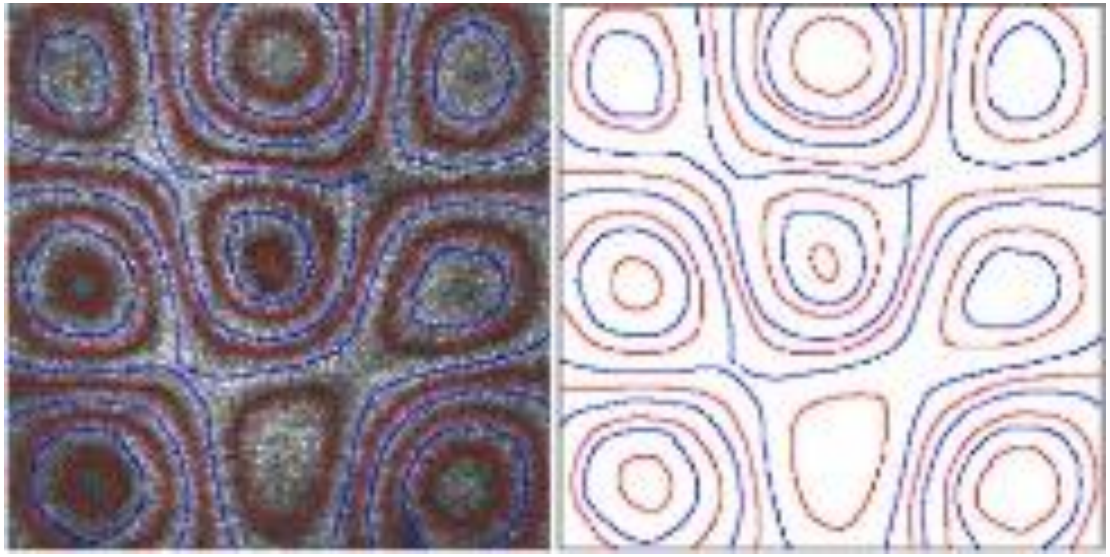
$n =$ is the fringe order

- A fringe represents a contour of constant phase
- n is the fringe order or "number of waves"

Fringe skeletonization

Sample: identification of fringe centers

Closed fringe pattern and continuous deformations:



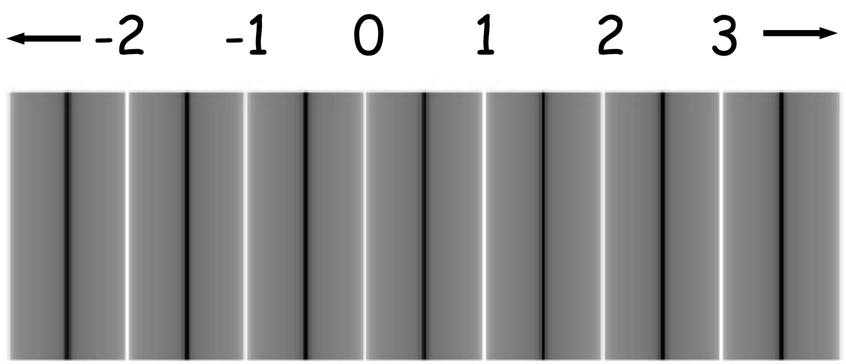
Fringe skeletonization

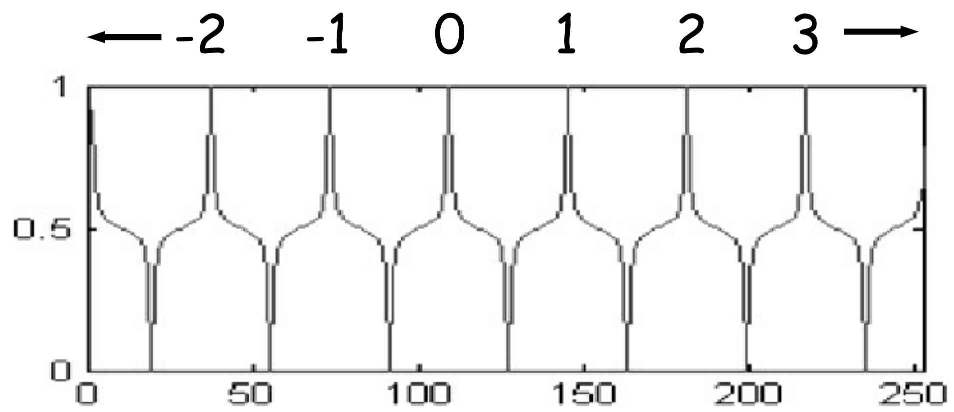
Fringe ordering: n-th order

- Identify zero-order: understanding of the physical phenomena
- Use sequential ordering

Fringe orders: n

Zero order

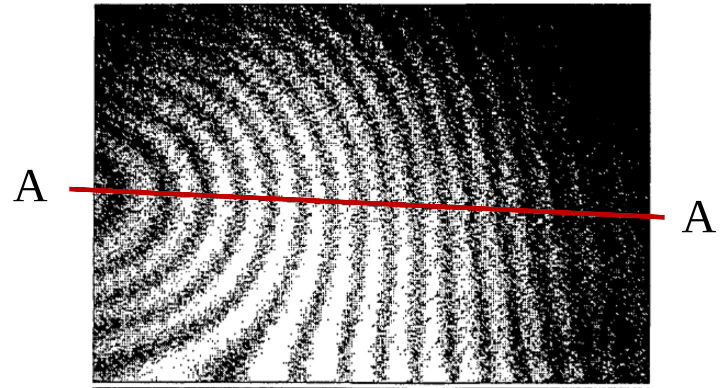




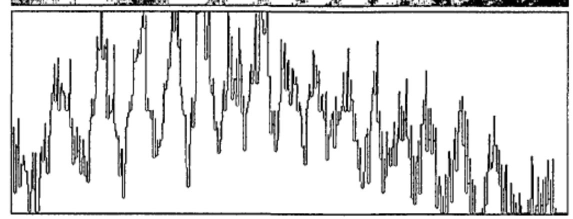
Fringe skeletonization

Fringe ordering

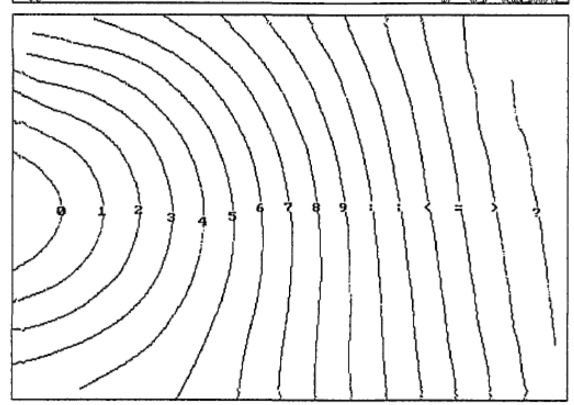
Opened fringe pattern and continuous deformations:



Intensity line: A-A



Fringe ordering:



Fringe skeletonization

Phase reconstruction

Fringe interpolation, e.g., Lagrange, Zernike polynomials, etc.

Lagrange polynomials of degree *n-1*

$$f(x_0) = \sum_{i=1}^{n} w_i(x_0) f(x_i)$$

$$w_i(x_0) = \frac{\prod_{\substack{j=1 \\ j \neq i}}^{n-1} (x_0 - x_j)}{\prod_{\substack{j=1 \\ j \neq i}}^{n-1} (x_i - x_j)}$$

$$f(x_0) = w_1(x_0) f(x_1) + w_2(x_0) f(x_2) + w_3(x_0) f(x_3) + \ldots + w_n(x_0) f(x_n)$$

Fringe skeletonization

Phase reconstruction

Fringe interpolation, e.g., Lagrange, Zernike polynomials, etc.

Lagrange polynomials of degree *n-1*

$$w_i(x_0) = \frac{\prod_{\substack{j=1 \\ j \neq i}}^{n-1} (x_0 - x_j)}{\prod_{\substack{j=1 \\ j \neq i}}^{n-1} (x_i - x_j)}$$

$$f(x_0) = \sum_{i=1}^{n} w_i(x_0) f(x_i)$$

$\underline{n = 2:}$

$$w_1(x_0) = \frac{x_0 - x_2}{x_1 - x_2}$$

$$w_2(x_0) = \frac{x_0 - x_1}{x_2 - x_1}$$

and

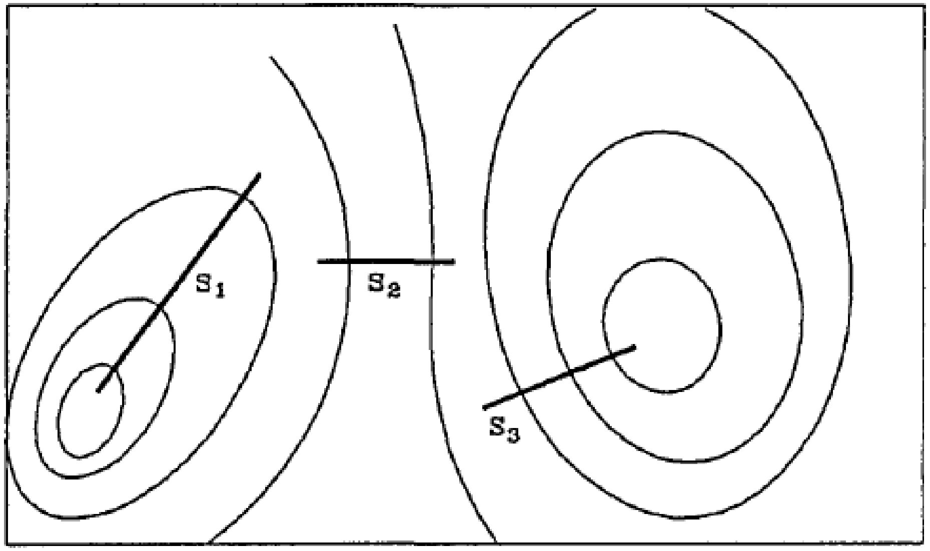
$$f(x_0) = w_1(x_0) f(x_1) + w_2(x_0) \cdot f(x_2)$$

$$= \frac{x_0 - x_2}{x_1 - x_2} f(x_1) + \frac{x_0 - x_1}{x_2 - x_1} f(x_2)$$

Fringe skeletonization

Phase reconstruction: **1-fringe** = $\lambda/2$

Reconstruction along specific lines:



Interpolation along specific lines: