Processing of binary fringe patterns obtained by phase-shifting time-averaged shearography on vibrating objects

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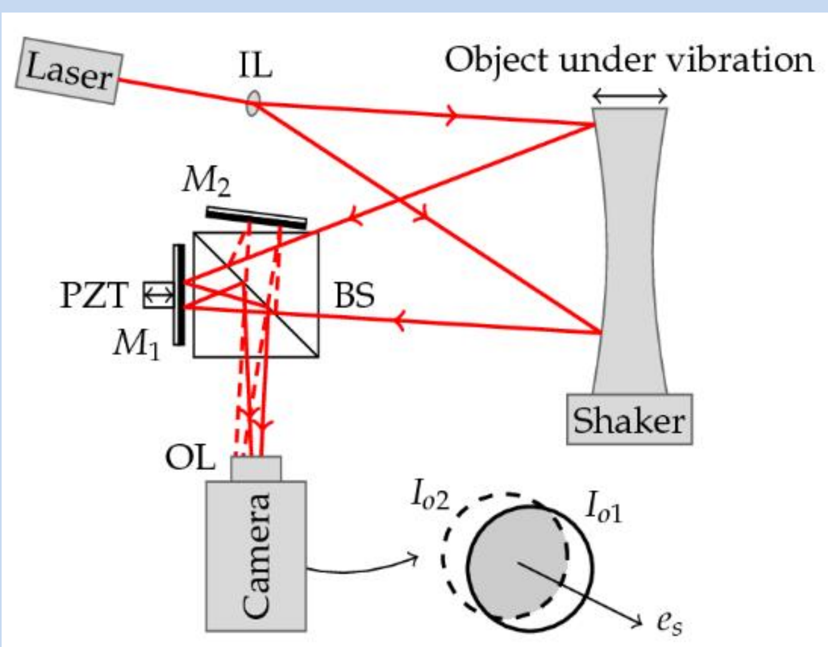
SUMMARY

Shearography is a full-field strain measurement technique which can be used in vibration analysis. In our case we apply a method which combines the time-averaging and phase-shifting techniques (PSTA). The PSTA method does not require shifting the phase of reference beam in synchronization with the object. A simple interferometer designed for usual NDT application can be used. PSTA produces binary phase patterns where the phase changes are related to the zeroes of a Bessel J_0 function, typical of time-averaging. However, the contrast and resolution are better compared to traditional time-averaging. In a previous paper, we have shown that this is particularly useful in vibration testing performed under industrial conditions because fringe patterns are noisier than in quiet laboratory environments. This works goes a step further in proposing a processing method for estimating the vibration amplitude, for helping non-experts to identify vibration modes. Since shearography measures the spatial derivative of displacement, spatial integration is required. Prior to that, different processes like denoising, binarization, automated nodal line detection and amplitude assignment are applied. Results are demonstrated on results obtained in laboratory and industrial conditions.

PHASE-SHIFTING TIME-AVERAGED SHEAROGRAPHY

D. Borza, "A new interferometric method for vibration measurement by electronic holography", Exp. Mech. **42** (4), 432-438 (2002)
D. Borza, "High-resolution time-average electronic holography for vibration measurement", Opt. Las. Eng.**41**, 515-527 (2004)



Instantaneous shearogram

$$I_{inst}(t) = I_{o1} + I_{o2} + I_m cos(\phi + \delta(t))$$

Phase difference due to vibration

$$\delta(t) = \delta_A \sin(\omega t)$$

Time-averaged shearograms

$$I = I_{o1} + I_{o2} + I_m J_0(\delta_A)\, cos(\phi)$$

Time-averaged shearograms with phase-shifting

$$I_k = I_{o1} + I_{o2} + I_m J_0(\delta_A) \cos(\phi + k\,\pi/2)$$

PHASE-SHIFTING OF REFERENCE BEAM
NO SYNCHRONIZATION WITH OBJECT !

At rest:

$$\phi_R = \tan^{-1}\left((I_{3,r} - I_{1,r})/(I_{0,r} - I_{2,r})\right)$$

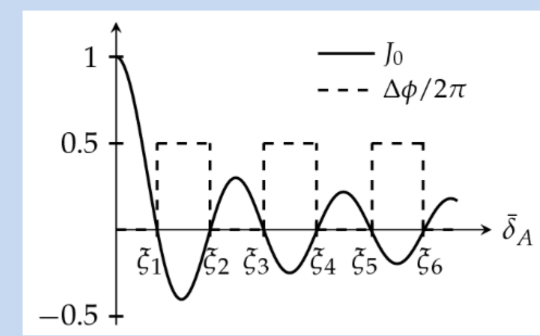
During vibration:

$$\phi_V = \tan^{-1}\left((I_3 - I_1)/(I_0 - I_2)\right)$$

Phase difference:

$$\Delta\phi = \phi_V - \phi_R = \begin{cases} 0 & \text{if } J_0(\delta_A) > 0 \\ \pi & \text{if } J_0(\delta_A) < 0 \\ \text{undefined} & \text{otherwise} \end{cases}$$

BINARY PHASE PATTERN



In shearography $\delta_A = \dfrac{\partial \varphi_A}{\partial s}\Delta_s$

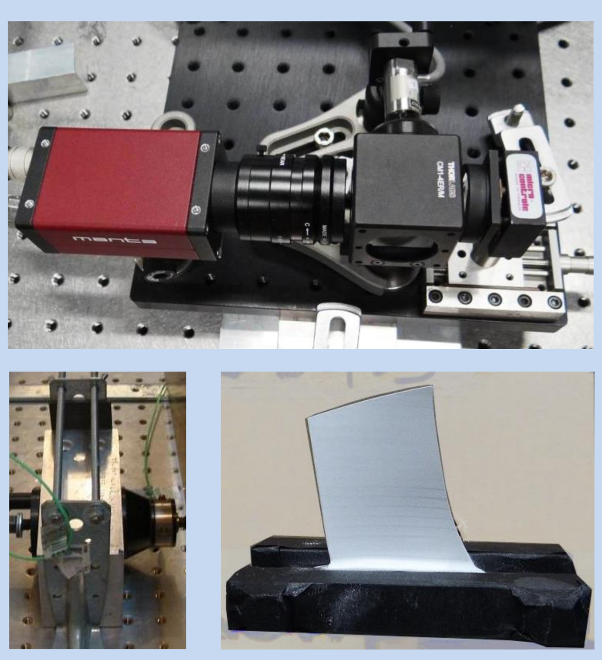
INTEGRATION NEEDED

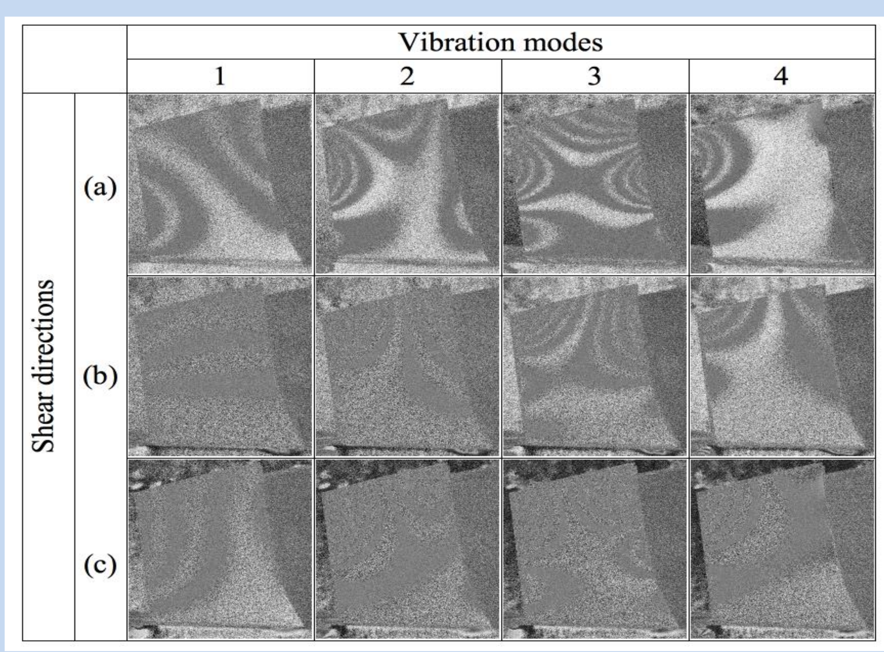
Vibration amplitude $\varphi_A = \displaystyle\int \frac{\delta_A}{\Delta_s}\, ds$

EXPERIMENTAL DATA USED IN PROCESSING

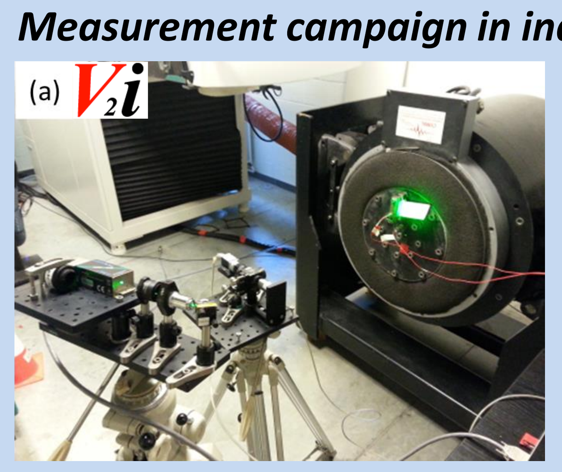
F. Languy, et al., "Vibration mode shapes visualization in industrial environment by real-time time-averaged phase-stepped electronic speckle pattern interferometry at 10.6 µm and shearography at 532 nm", Opt. Eng. **55** (12), 121704 (2016)

Measurement campaign in the lab



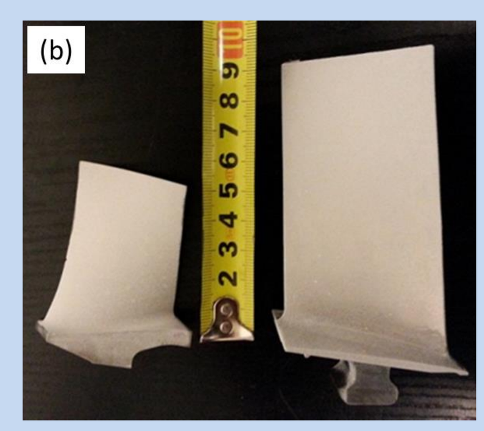


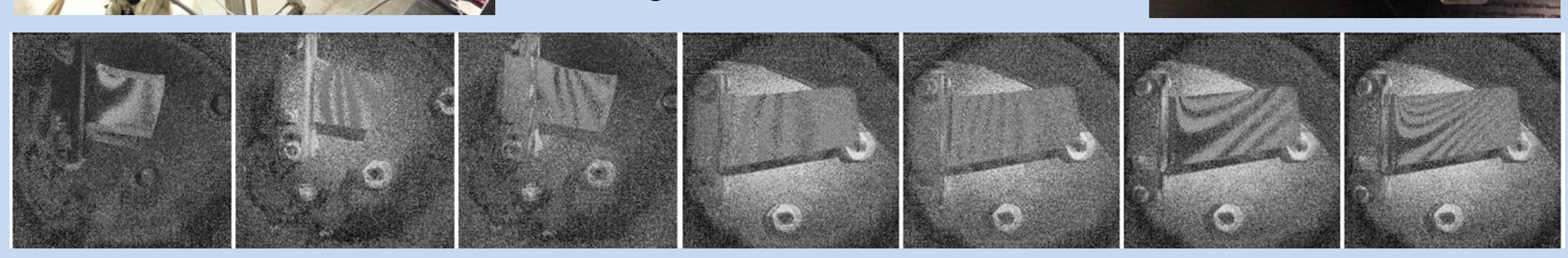
Measurement campaign in industrial environment



(a) Electrodynamic shakers were used in industrial testing
Noise sources are present: acoustic, air turbulences related to cooling fan, floor vibrations

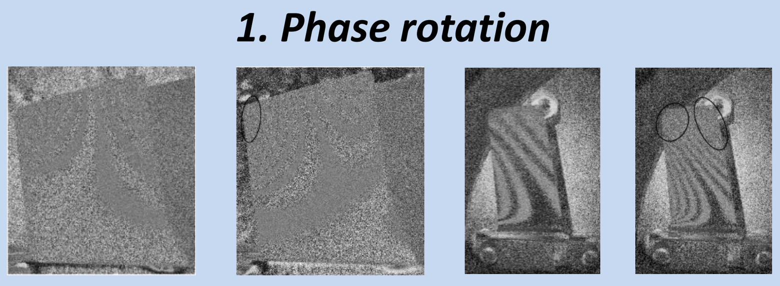
(b) Two compressor blades were investigated in these conditions

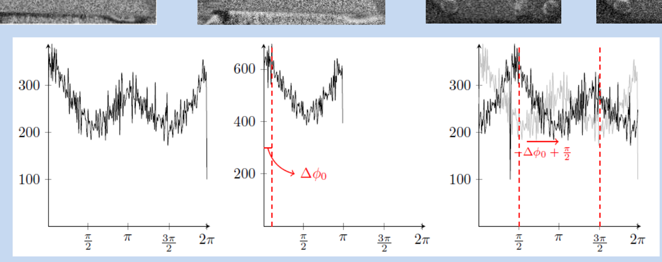




PRE-PROCESSING: PHASE ROTATION AND DENOISING

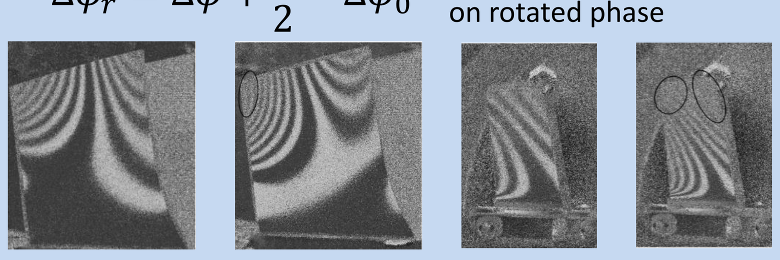
1. Phase rotation



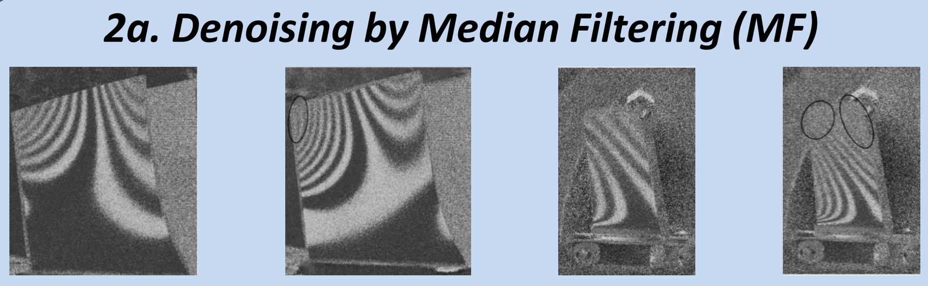


$$\Delta\phi_r = \Delta\phi + \frac{\pi}{2} - \Delta\phi_0$$

Noise has smaller impact on rotated phase

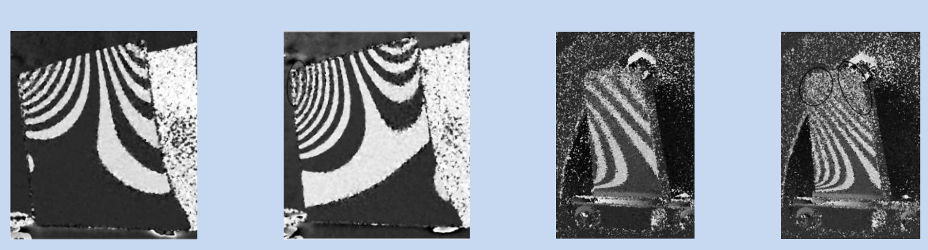


2a. Denoising by Median Filtering (MF)

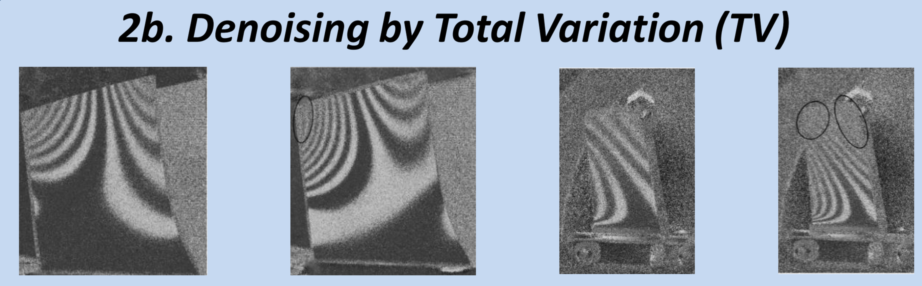


Median filtering M_f applied on sine and cosine functions. It is the usual filtering used in speckle-based methods

$$\Delta\phi_p = \tan^{-1}\left[\frac{M_f(\sin\Delta\phi_r)}{M_f(\cos\Delta\phi_r)}\right]$$



2b. Denoising by Total Variation (TV)

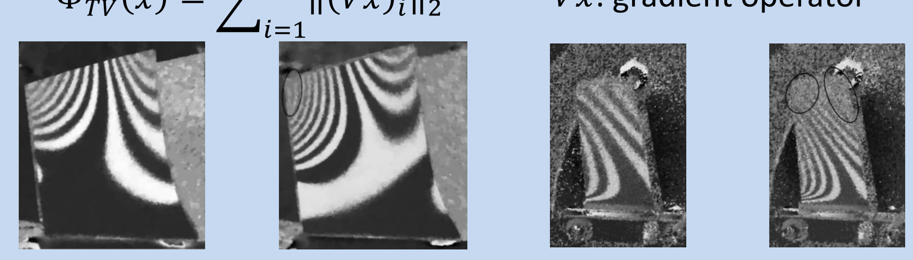


Fringes with excessive and possibly spurious details have high total variation (TV), i.e. the gradient integral is high. Reducing the noise requires to decrease the TV

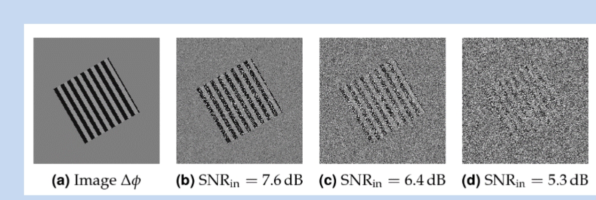
$$\Delta\phi_p = \arg min_x \|x - \Delta\phi_r\| + \alpha\Phi(x)$$

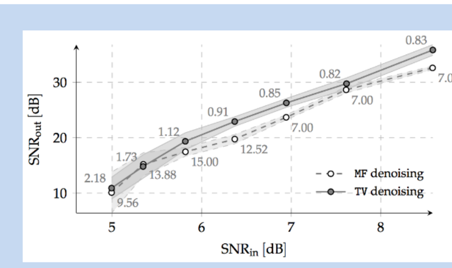
$$\Phi_{TV}(x) = \sum_{i=1}^{N} \|(\nabla x)_i\|_2$$

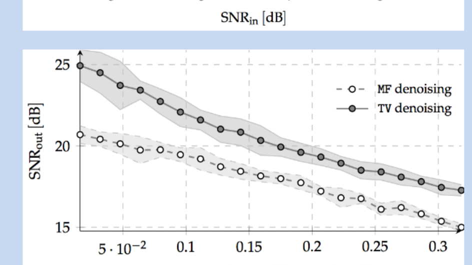
∇x: gradient operator



Comparison of denoising techniques
Based on synthetic data







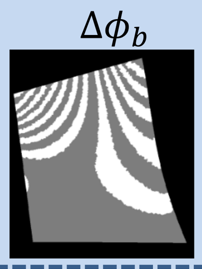
PROCESSING: ESTIMATION OF VIBRATION AMPLITUDE

1. Binarization of $\Delta\phi_p$

$\Delta\phi_p$

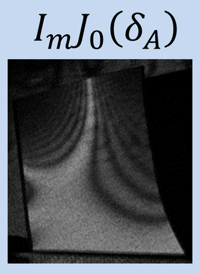
1) Delineation by thresholding
2) Region-size filtering
(too small areas are eliminated)

$\Delta\phi_b$



2. Automatic detection of nodal lines on $I_m J_0(\delta_A)$

$I_m J_0(\delta_A)$

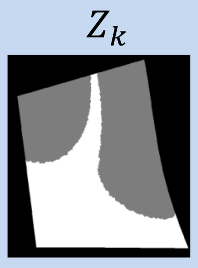


1) Calculation of time-averaged image

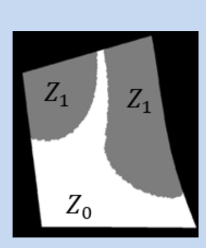
$$I_m J_0(\delta_A) = \frac{1}{2}\sqrt{[(I_3 - I_1)^2 + (I_0 - I_2)^2]}$$

2) Determination of Z_k, zero-crossing regions, based on the fact that SNR of $\Delta\phi_r$ and $I_m J_0(\delta_A)$ is maximized in this region

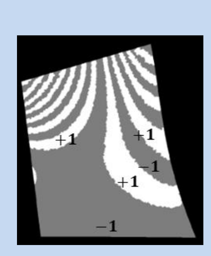
Z_k

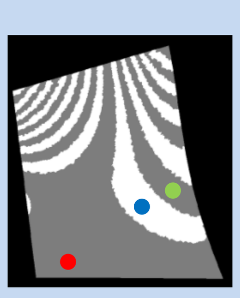


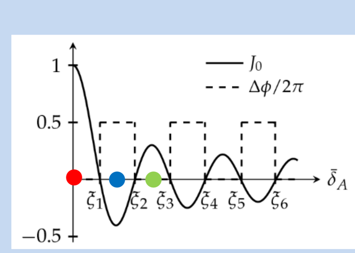
3. Labelling of δ_A

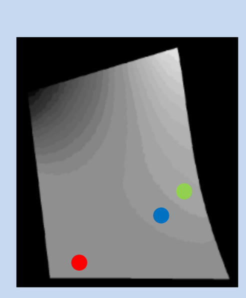


1) Before determination of δ_A, we need to assign a sign at each phase change
2) Each Z_k has 2 adjacent regions with opposite signs of δ_A
3) At each region with changing sign, we attribute a value of δ_A







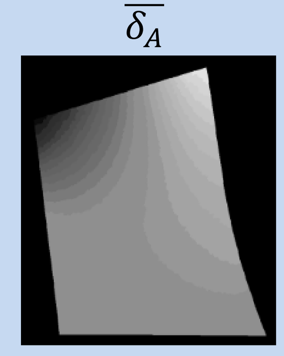


4. Calculation of amplitude φ_A

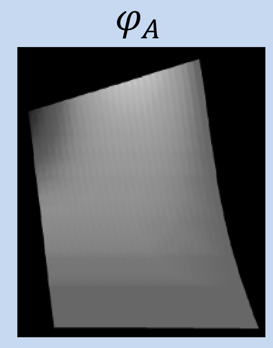
Integration followed by mean-filtering are performed

$$\varphi_A = \int \frac{\delta_A}{\Delta_s}\, ds = \overline{\delta_A}\, \text{sign}(\delta_A)$$

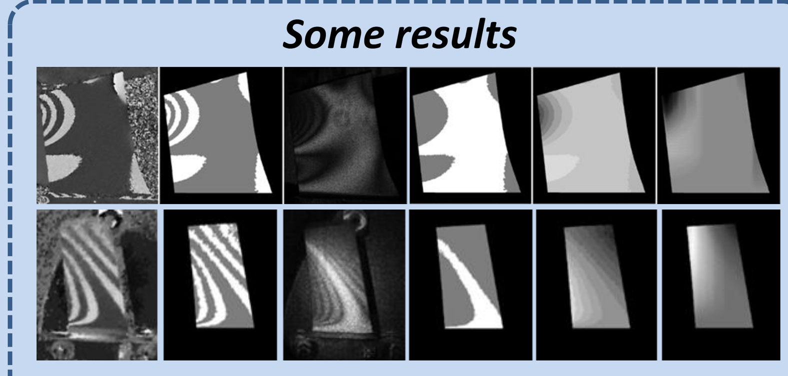
$\overline{\delta_A}$



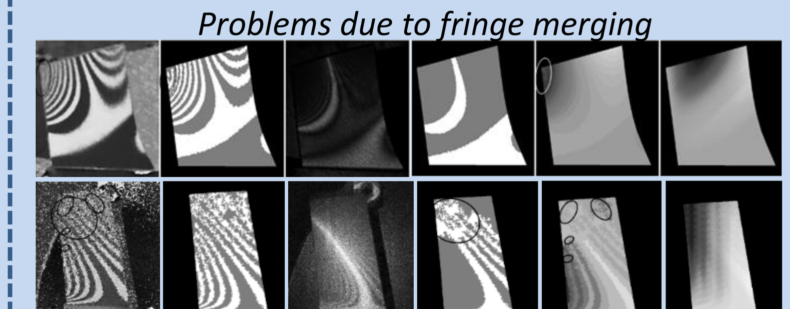
φ_A



Some results



Problems due to fringe merging



CONCLUSIONS

PSTA shearography allows easy capture of shearograms of vibrating objects. The binary phase fringe pattern can be processed up to obtain amplitude of vibrations. However this requires pre-processing for denoising and the results may suffer from fringe merging.

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