Accuracy improvement in digital holographic-based speckle correlation for three-dimensional (3D) displacement measurement

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Outline

- Introduction
  - The combination of digital holographic interferometry (DHI) and digital speckle photography (DSP)
  - Our research work: In digital holography, how to get an accurate in-plane displacement result using DSP?
- Theoretical analysis: sources of error
- Experimental results
- Conclusions and discussion

Introduction

The combination of digital holographic interferometry (DHI) and digital speckle photography (DSP)

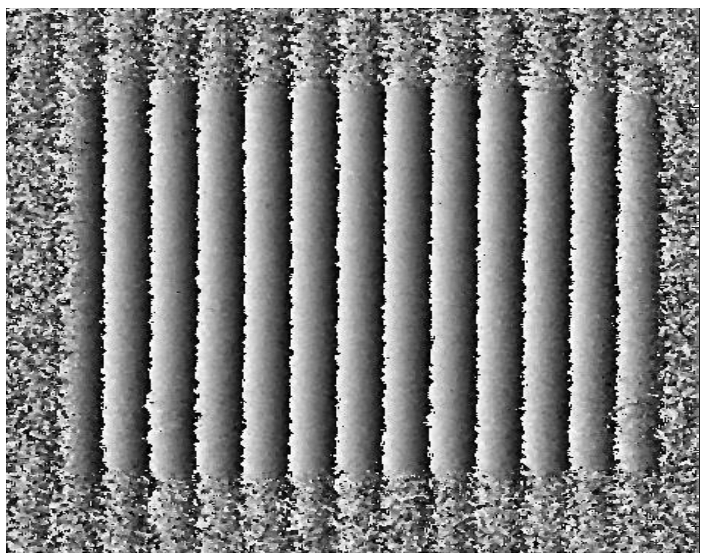
Initial object → Holograms recording ← Displaced object

Holograms recording → Numerical reconstruction

Digital Holography

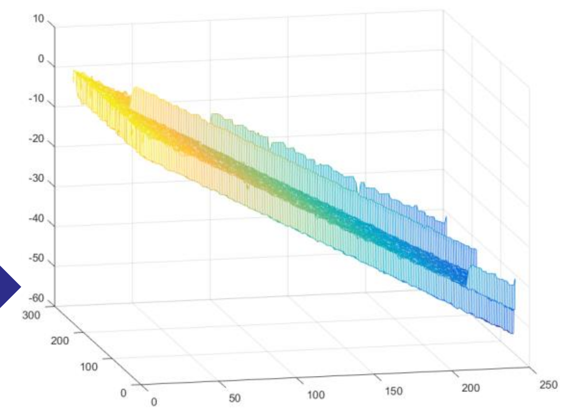
Initial amplitude A_{ini}	Initial phase φ_{ini}	Displaced phase φ_{disp}	Displaced amplitude A_{disp}

digital holographic interferometry (DHI)



Phase difference

$(\varphi_{disp} - \varphi_{ini})$



Out-of-plane displacement

Introduction

The combination of digital holographic interferometry (DHI) and digital speckle photography (DSP)

Initial object

Holograms recording

Numerical reconstruction

Digital Holography

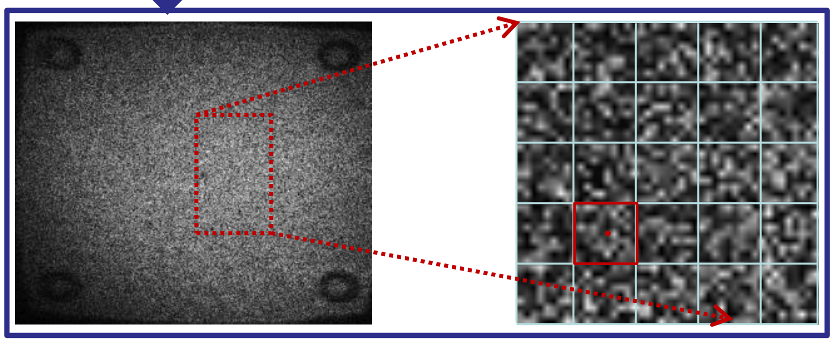
Displaced object

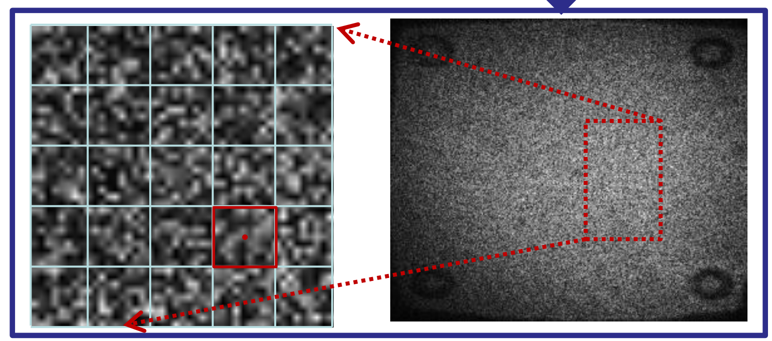
Initial amplitude A_{ini}

Initial phase φ_{ini}

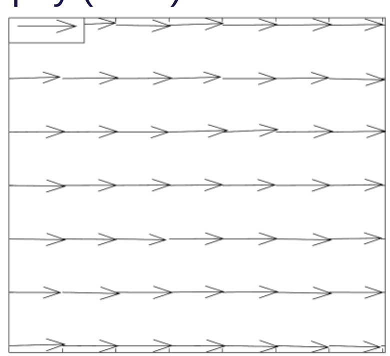
Displaced phase φ_{disp}

Displaced amplitude A_{disp}





digital speckle photography (DSP)



In-plane displacement

The combination of digital holographic interferometry (DHI) and digital speckle photography (DSP)

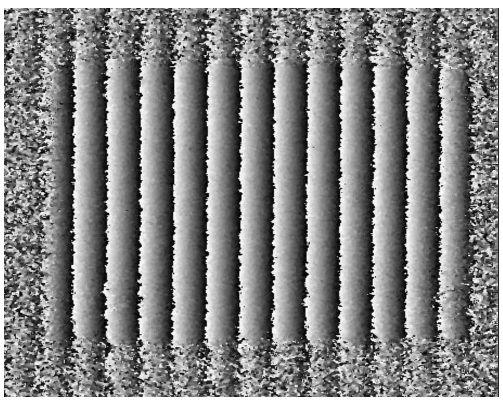
Initial object → Holograms recording ← Displaced object

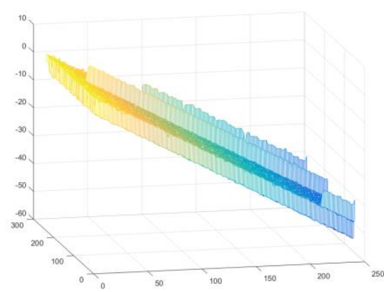
Holograms recording → Numerical reconstruction

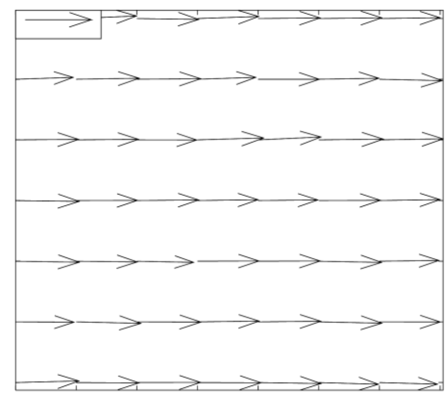
Digital Holography

Numerical reconstruction → Initial phase φ_{ini}, Initial amplitude A_{ini}

Numerical reconstruction → Displaced phase φ_{disp}, Displaced amplitude A_{disp}







Out-of-plane displacement

In-plane displacement

Non-contact 3D displacement measurement

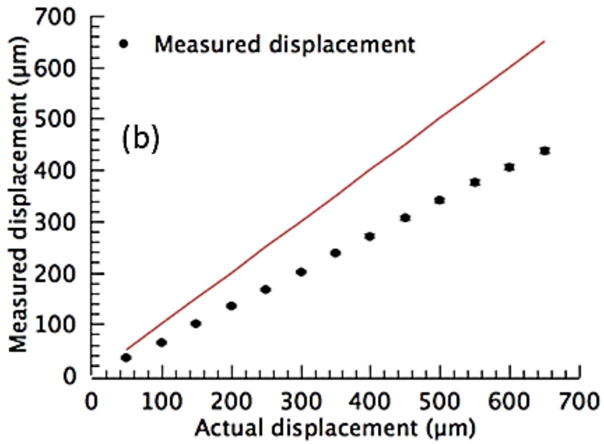
Introduction

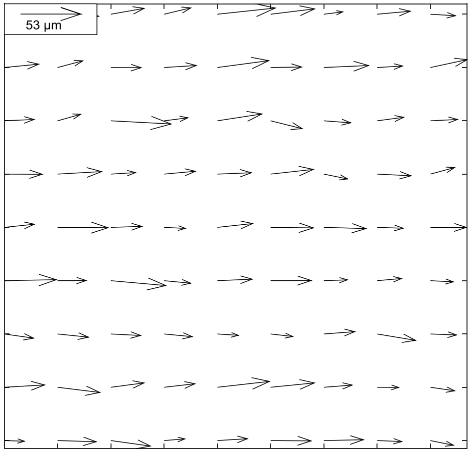
Subject

Implement DSP based on amplitudes reconstructed from **Fresnel DH** for in-plane displacement measurement.

Existing problem

DH-based DSP produced **inaccurate in-plane measurement (under/over estimation)** and **large deviation** compared with classical DSP result.





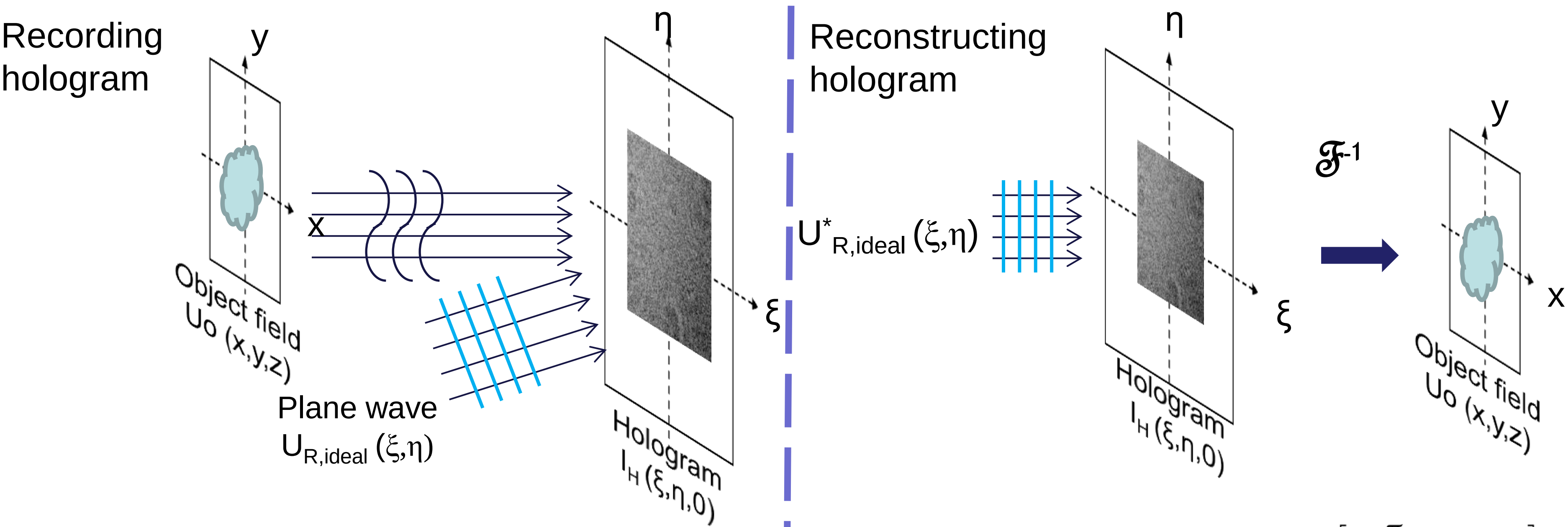
Same problems have been reported in other publications.

Hypotheses

Sources of error leading to inaccurate in-plane measurement result:

1. **Phase errors** existing in reference wave cause extra speckle displacement
2. **Speckle size** on reconstruction plane doesn't satisfy **sampling criteria**

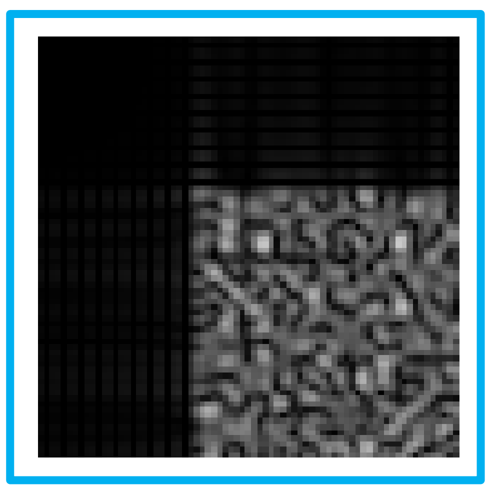
Phase errors in reference wave



$$U_{R,\ ideal}(\xi,\eta) = R_0$$

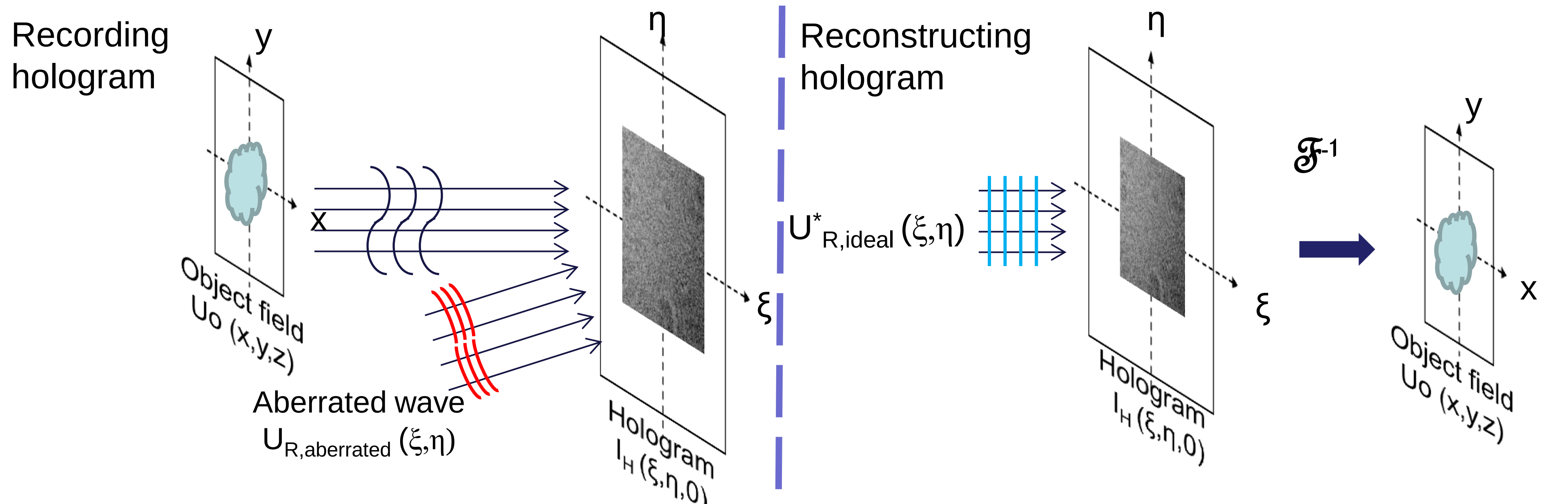
$$U_O(x,y,z) = \mathscr{F}^{-1}\left\{U^*_R(\xi,\eta)\, I_H(\xi,\eta) \exp\left[-\mathrm{i}\frac{\pi}{\lambda z}\left(\xi^2+\eta^2\right)\right]\right\}$$

Simulated recording and reconstruction process without phase error



- Reconstructed image without phase error
- Speckle moves with the object
- Speckle displacement represents object displacement

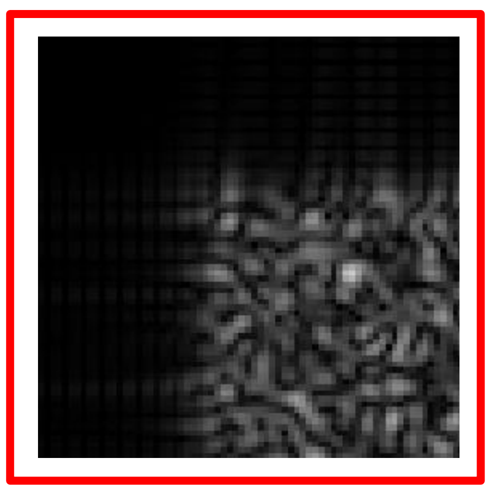
Phase errors in reference wave



$$U_{R,\ aberrated}\left(\xi,\eta\right) = R_0 \exp\left[-\mathrm{i}\left(a\xi^2 + b\eta^2 + c\xi + d\eta\right)\right]$$

$$U_O\left(x,y,z\right) = \mathscr{F}^{-1}\{U^*{}_R\left(\xi,\eta\right) I_H\left(\xi,\eta\right) \exp\left[-\mathrm{i}\frac{\pi}{\lambda z}\left(\xi^2+\eta^2\right)\right]\}$$

Simulated recording and reconstruction process with phase error



- Reconstructed image with phase error
- Speckle doesn’t move with the object.
- Defocused object field causes complementary speckle displacement

Speckle size and sampling criteria

Second hypothesis

Speckle size on reconstruction plane doesn't satisfy sampling criteria.

❑ In **classical** DSP:

- Speckle size should be ≥ 2 pixels
- If Speckle size < 2 pixels

→ Systematic errors: a drift toward the closest integral pixel value

→ Speckle size adjustment : changing aperture of imaging system

Sjodahl, M. and L. R. Benckert (1994). "Systematic and random errors in electronic speckle photography." Appl Opt 33(31): 7461-7471.

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❑ In **Fresnel DH**-based DSP

One speckle grain occupies one pixel

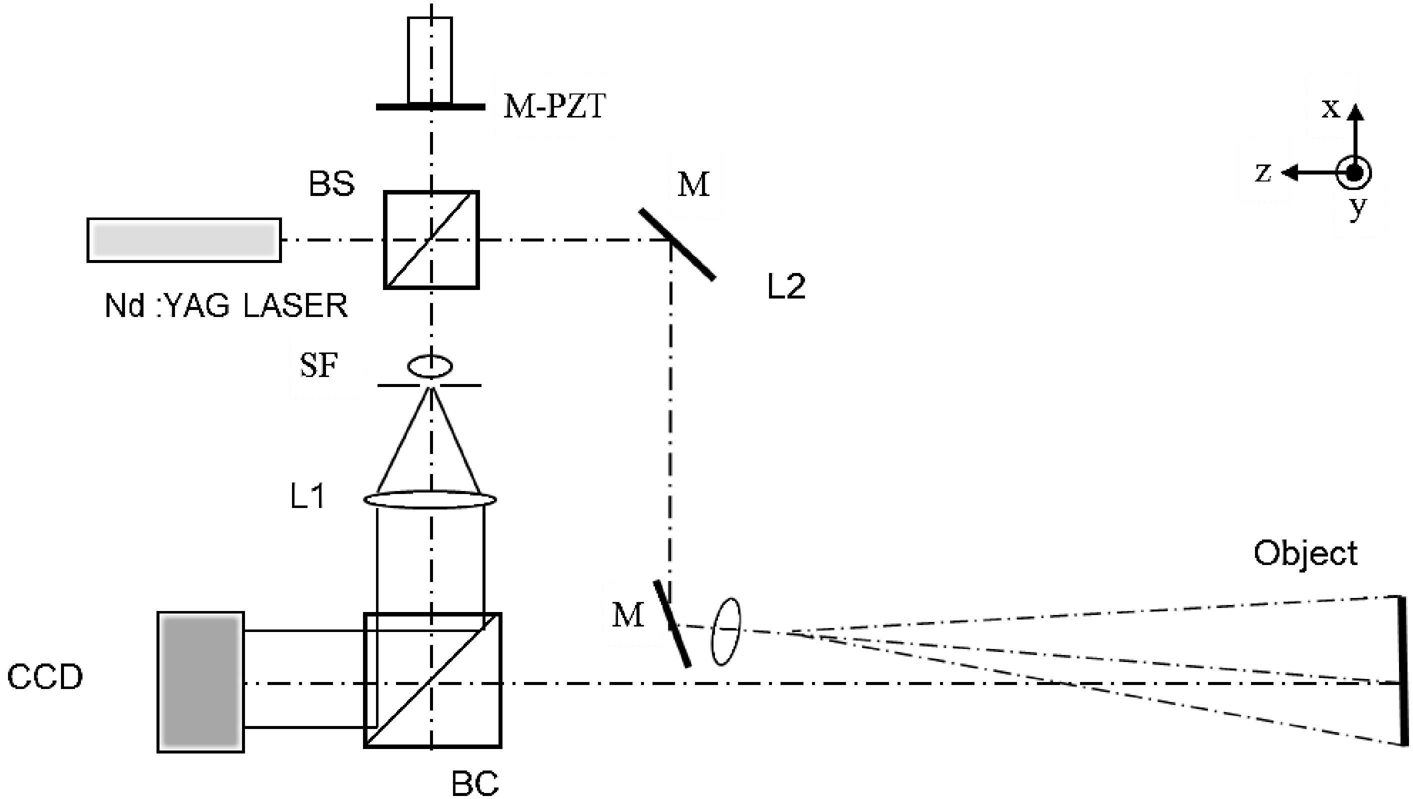
$$\sigma_x = \frac{\lambda z}{D_x}; \quad \sigma_y = \frac{\lambda z}{D_y}$$

$$\Delta x = \frac{\lambda z}{M \Delta \xi}; \quad \Delta y = \frac{\lambda z}{N \Delta \eta}$$

$$\sigma_x = \Delta x; \quad \sigma_y = \Delta y$$

Speckle size should be adjusted to eliminate systematic errors!

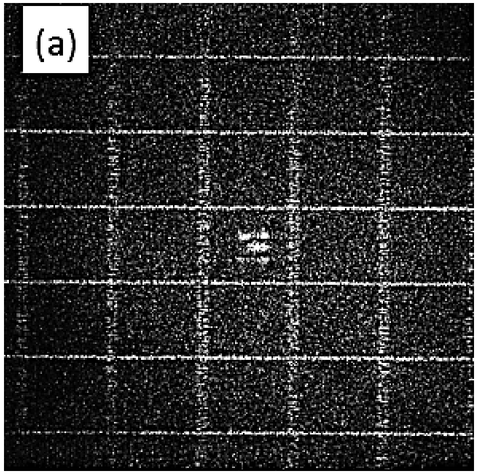
Experimental setup



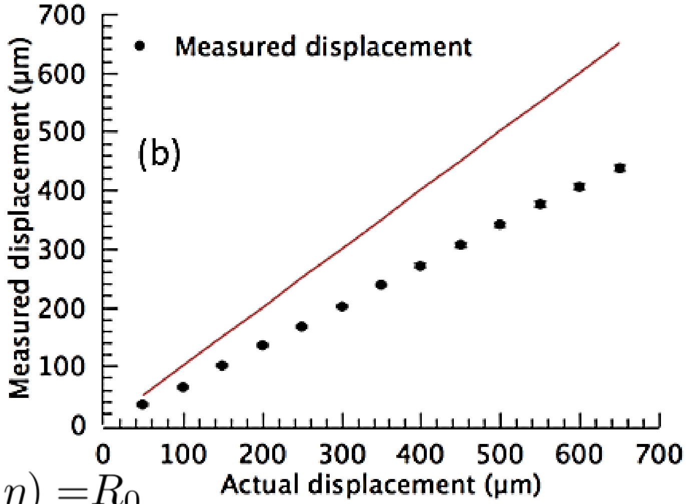
- In-line DH, Phase stepping for eliminating twin images
- The CCD contains 480 ×480 pixels
- Diffusing object: 5 cm
- Fresnel reconstruction with a single FFT

Results

Under-estimated results are obtained without considering phase errors correction.

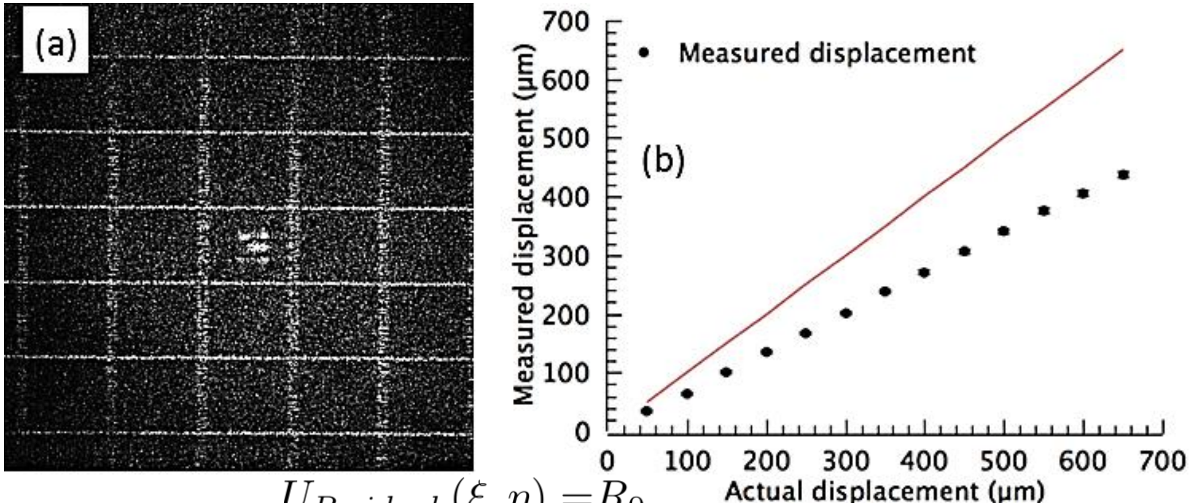


$$U_{R,\ ideal}\,(\xi,\eta) = R_0$$



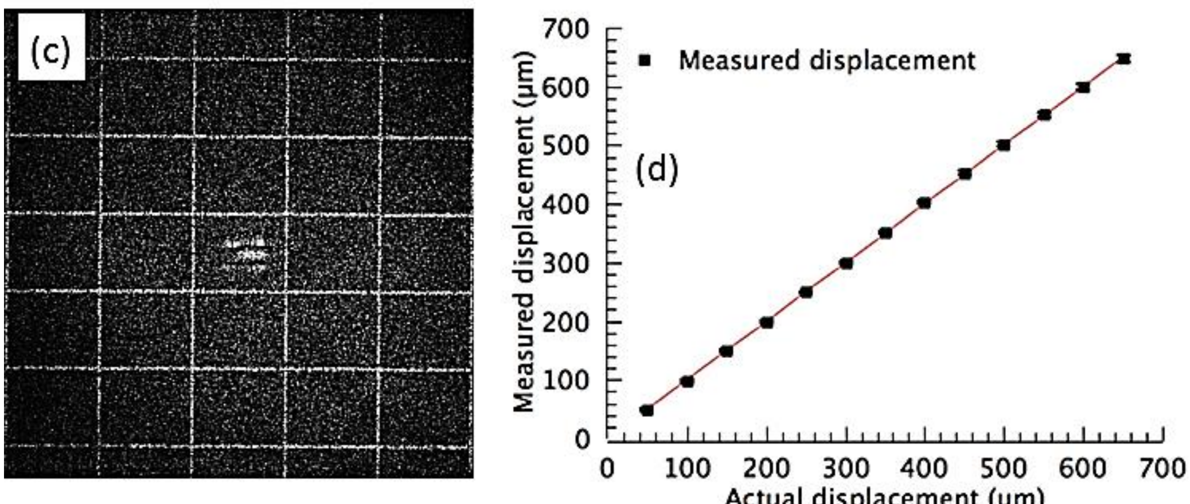
When the phase error hasn't been corrected, the hologram is reconstructed by $U_{R,\ ideal}$, the measured result is **under-estimated.**

DSP measured results match the actual displacement after phase errors are corrected



$$U_{R,\ ideal}\left(\xi,\eta\right) = R_0$$

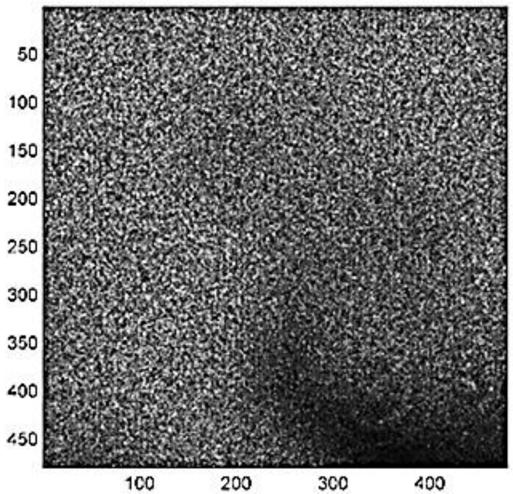
When the phase error hasn't been corrected, the hologram is reconstructed by $U_{R,\ \text{ideal}}$, the measured result is **under-estimated.**



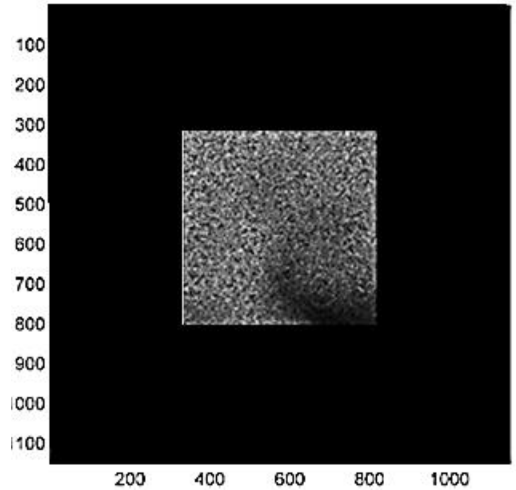
$$U_{R,\ aberrated}\left(\xi,\eta\right) = R_0 \exp\left[-\mathrm{i}\left(a\xi^2 + b\eta^2 + c\xi + d\eta\right)\right]$$

The quadratic phase error is **corrected**, the hologram is reconstructed by $U_{R,\ \text{aberrated}}$, the measured result matches actual displacement

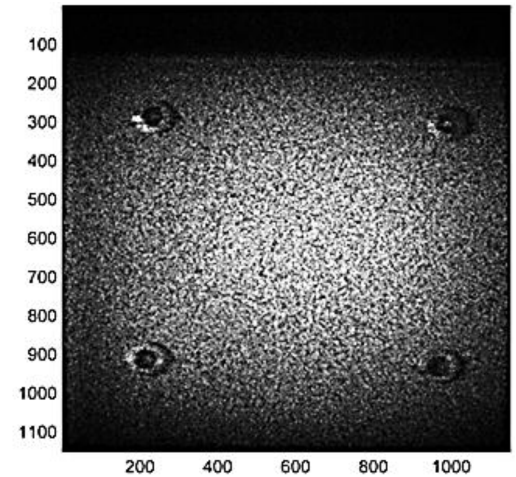
Zero-padding the hologram can change the pixel size on reconstructed plane, thus changing the speckle size in term of pixels.



I_0 (480×480)



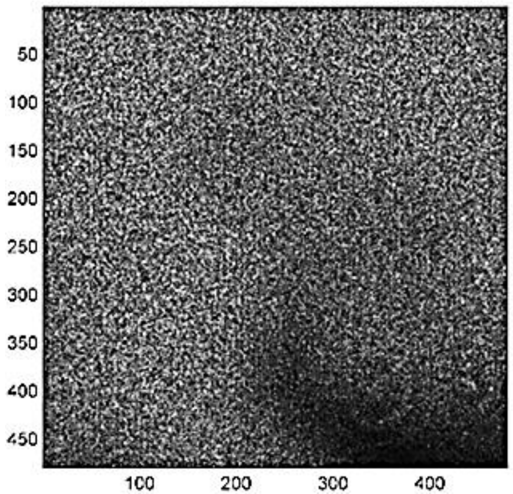
I_{zp} (1152×1152)



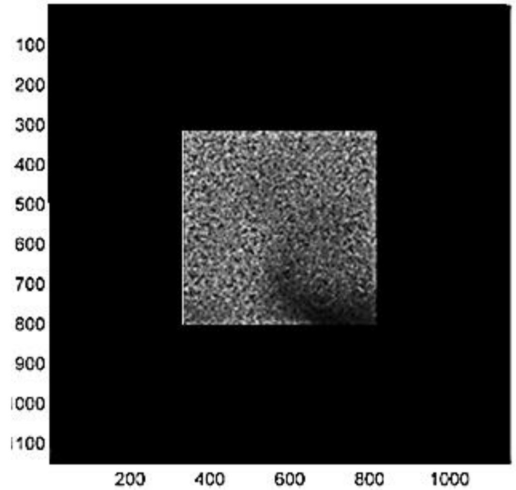
U_{zp} (1152×1152) reconstructed from I_{zp}

Results

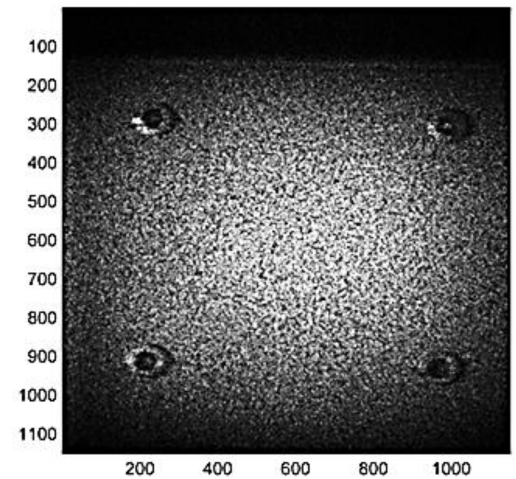
Zero-padding the hologram can change the pixel size on reconstructed plane, thus changing the speckle size in term of pixels.



I_0 (480×480)

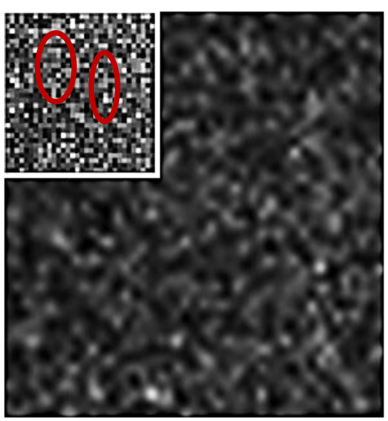


I_{zp} (1152×1152)

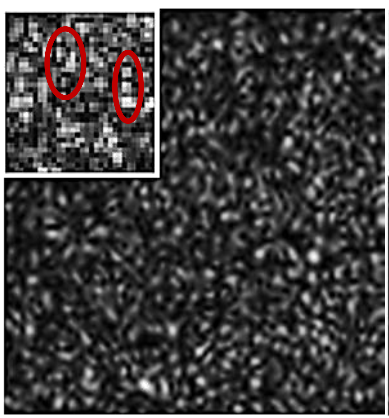


U_{zp} (1152×1152) reconstructed from I_{zp}

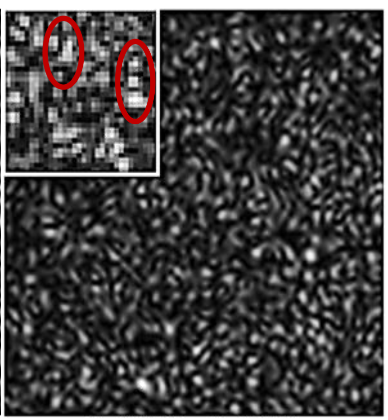
Zoom of reconstructed area



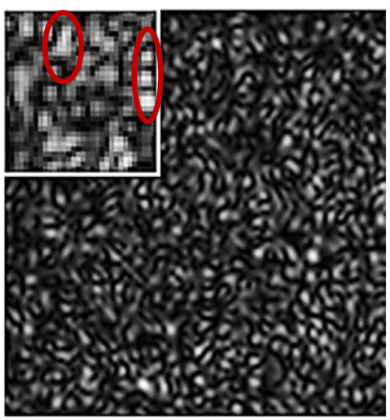
480×480



960×960



1152×1152

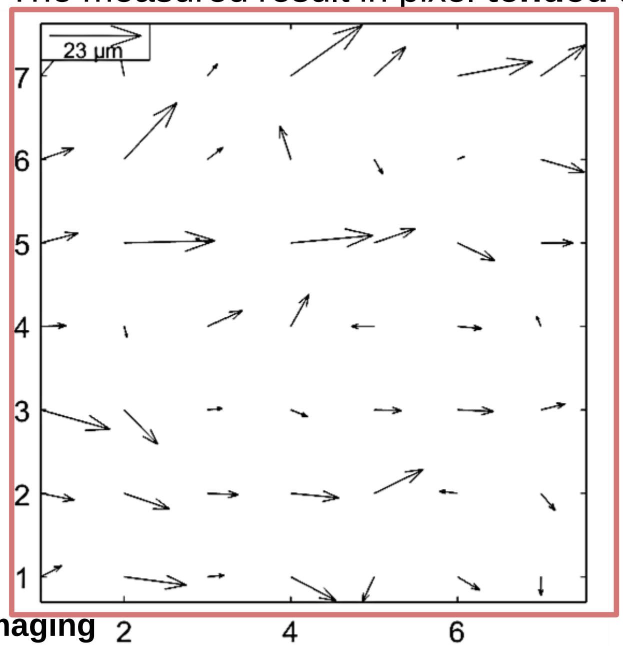


1440×1440

Inaccurate results are obtained without adjusting speckle size.

	Zero-padding case	Speckle size	Applied translation (µm)	Measured result (µm)	Applied translation (px)	Measured result (px)
Before zeropadding	**480×480**	155.8 µm =1 px	50	7.206±6.391	0.321	0.047±0.041
			100	148.1±3.554	0.642	0.951±0.045
			150	155.6±4.512	0.963	0.999±0.029
			200	162.5±8.125	1.283	1.043±0.052

- **Systematic errors** are observed when no zero-padding has been applied (**speckle size ≤ 2px**).
- The measured result in pixel **tended to round** the actual displacement.

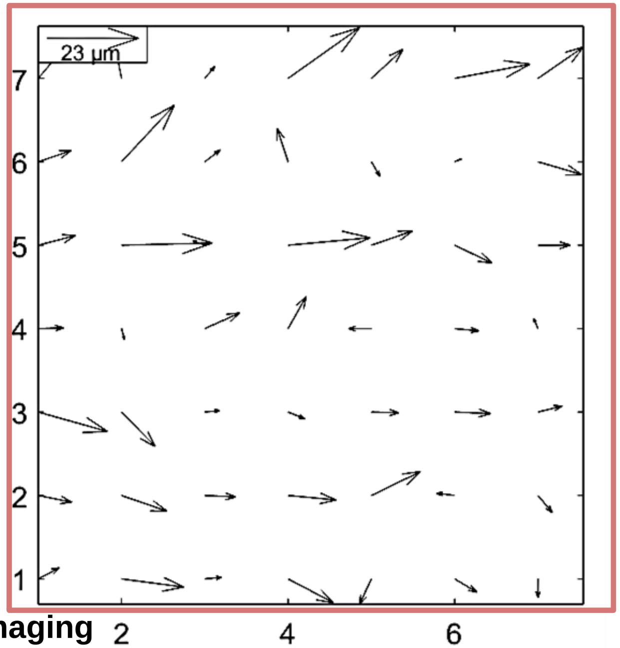


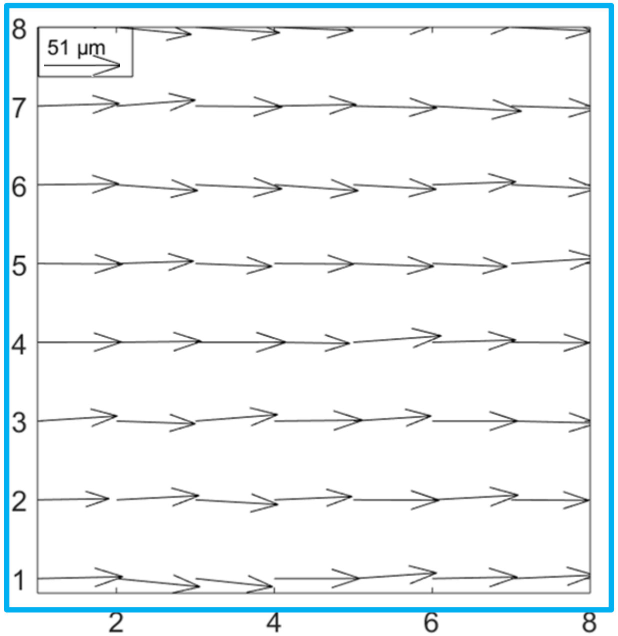
Results

Accurate results are obtained after adjusting speckle size via zero-padding.

	Zero-padding case	Speckle size	Applied translation (μm)	Measured result (μm)	Applied translation (px)	Measured result (px)
After zeropadding	**1152 ×1152**	155.8 μm =2.4 px	50	51.10±2.708	0.770	0.787±0.042
			100	98.70±2.369	1.540	1.520±0.074
			150	149.1±4.622	2.310	2.296±0.069
			200	199.2±3.785	3.080	3.067±0.059

- Systematic errors are **eliminated** when speckles are **larger than 2 pixels**. Standard deviation is comparable to classical DSP.





Conclusions and discussion

- Intrinsic properties of Fresnel DH reconstruction contribute to inaccurate in-plane displacement measurement results using DSP
  - Phase errors lead to complementary displacements.
  - Speckle size leads to systematic errors.

- The accuracy of in-plane measurement is improved after correcting sources of error, comparable to classical DSP

- Measurable range should be taken into consideration in 3D measurement
  - In-plane: several tens of speckle diameter with subpixel accuracies
  - Out-of-plane: range of interferometry (λ) and the number of fringes that can be resolved

Thank you for your attention!

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Appendix

Table 1: Comparison of DSP measurement results under various zero-padding levels

Zero-padding N	Speckle size (px) σ_x	Applied Translation (µm) d_x	Applied Translation (px) k_x	Average result (px) $\overline{k_x}$	std (px) s_k	Average result (µm) $\overline{d_m}$	std (µm) s_d
480	1	50	0.321	0.047	0.041	7.026	6.394
480	1	100	0.642	0.951	0.045	148.1	3.554
480	1	150	0.963	0.999	0.029	155.6	4.512
480	1	200	1.283	1.043	0.052	162.5	8.125
960	2	50	0.642	0.688	0.041	53.60	3.377
960	2	100	1.283	1.200	0.036	93.53	1.403
960	2	150	1.925	1.906	0.037	152.8	2.903
960	2	200	2.567	2.619	0.073	204.1	5.715
1152	2.4	50	0.770	0.787	0.042	51.10	2.708
1152	2.4	100	1.540	1.520	0.074	98.70	2.369
1152	2.4	150	2.310	2.296	0.069	149.1	4.622
1152	2.4	200	3.080	3.067	0.059	199.2	3.785
1440	3	50	0.963	0.911	0.067	47.30	3.500
1440	3	100	1.925	1.889	0.071	98.13	1.864
1440	3	150	2.889	2.888	0.092	149.9	1.499
1440	3	200	3.850	3.841	0.102	199.5	5.367

- Larger speckles lead to larger random error.
  Speckle size = 2.4 px gives satisfactory results.