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Removal of optical aberrations caused by illumination system in Fourier ptychography

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ABSTRACT

The Fourier ptychographic microscopy (FPM) algorithm provides a method for reconstructing a high resolution image by stitching together the Fourier spectra of a number of low resolution intensity images, which are taken under various inclined illumination angles. However, the quality of the reconstructed image can be distorted by the optical aberrations of the illumination system. In this paper we investigate the influence of the optical aberrations on the reconstructed intensity images by using the FPM algorithm and discuss whether is it possible to remove the optical aberrations of the illumination system.

Index Terms - Fourier ptychography, illumination aberration, resolution, reconstructed image

1. INTRODUCTION

The Fourier ptychographic microscopy (FPM) algorithm reconstructs a high resolution complex sample image by combining the Fourier spectra of a number of individually measured low resolution intensity images [1]. This stitching of the individual Fourier spectra becomes possible by applying the phase retrieval concept developed by Fienup [1, 2]. However, in practice the imperfections of the optical system distort the quality of the reconstructed image. Here we investigate the effect of distortions in the illumination wavefronts on the quality of the reconstruction.

The paper is structured as follows. In Section 2 we introduce the theory of Fourier optics and Fourier ptychography. In Section 3 we analyze the error sources of an optical system in practice and focus on the influence of the illumination aberrations on the quality of the reconstructed intensity image by using the FPM algorithm. In Section 4 we discuss whether is it possible to remove the optical aberrations in the illumination system. A conclusion is drawn in Section 5.

2. FOURIER OPTICS AND PTYCHOGRAPHY

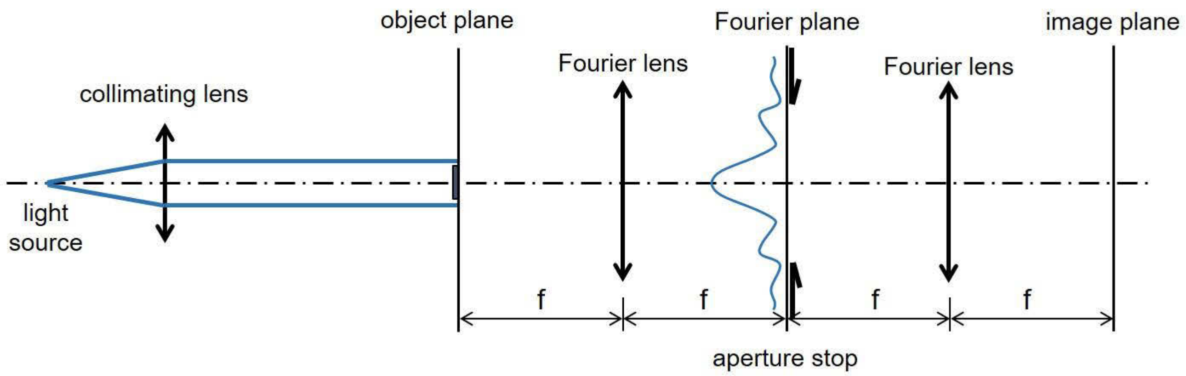

Figure 1: An illustration of the typical coherent imaging system in Fourier optics [3]

Figure 1 shows an illustration of the typical coherent 4f-imaging system in Fourier optics with an illumination beam [3]. Here we use a spoke target, which has 16 bars over 360° as the sample object for the resolution test. In the Fourier plane there is an aperture stop which effectively limits the Fourier spectrum of the object (spoke target) transmitted through the imaging system.

Due to this finite aperture the intensity distribution in the image corresponds to only a portion of the Fourier spectrum. Different illumination angles lead to different phase shifts in the spatial domain. Hence, if the illumination angle is varied, another section of the Fourier spectrum of the object is transmitted. Thus a modified intensity distribution is recorded in the image plane for each illumination angle. By stitching together the Fourier spectra of the individually recorded images properly, we can obtain an extended Fourier spectrum and thus a higher resolution in the reconstructed image. To this end the missing phase information of the recorded intensity images needs also to be recovered, e.g., with an appropriated phase retrieval algorithm. The algorithm consisting of the stitching process in the Fourier domain and an iterative phase retrieval procedure is the so-called FPM algorithm [1]. The FPM algorithm requires overlaps between every two neighboring Fourier spectra and a sketch of the algorithm is shown in Figure 2 A [4].

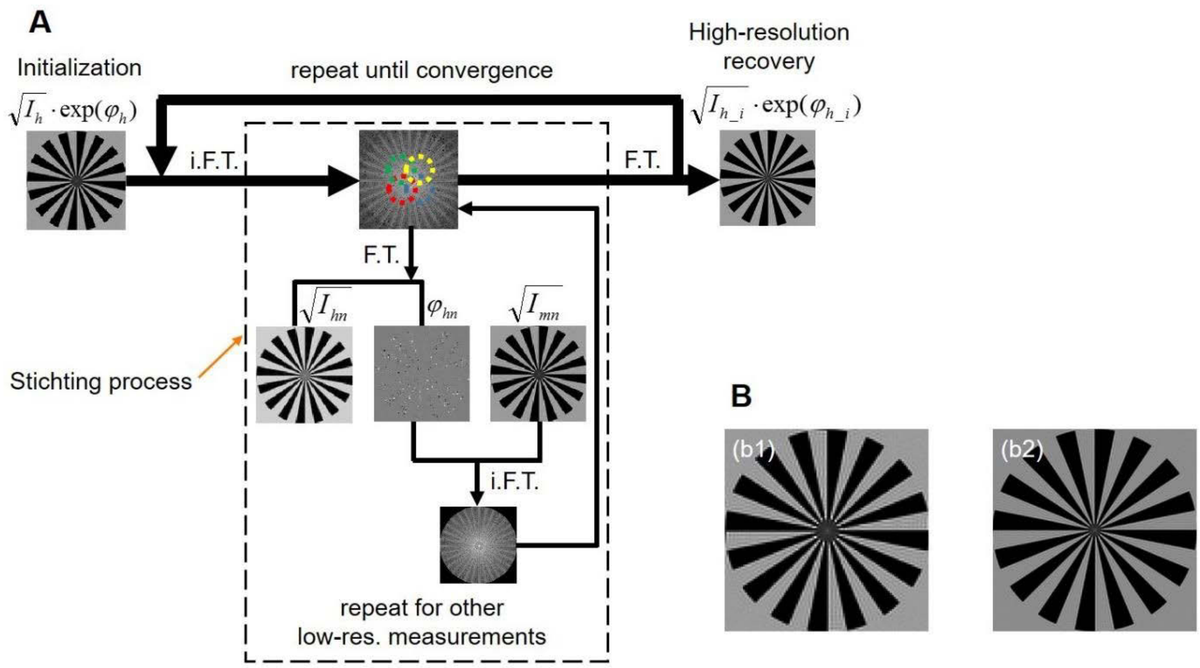

Figure 2: FPM algorithm. A: Schematic of the FPM algorithm. B: Comparison of a reconstructed high resolution intensity image (b2) with a recorded low resolution intensity image (b1). The words "F.T." and "i.F.T." denote the Fourier transform and the inverse Fourier transform, respectively. [4]

In each iteration, the stitching process replaces the amplitude of the Fourier transform of the Fourier spectrum in each subregion with the square root of the measured intensity while the phase information remains unchanged. We continue this iterative phase retrieval process until it converges to a stable solution.

In the idealized situation the illumination waves for different angles have identical and uniform intensities as well as plane wavefronts, the imaging system and the images are aberration free. Moreover, there are no image noise and misalignments. Simulations show that after using the Fourier ptychography algorithm with 100 iterations, we can get a higher resolution image (b2), compared to a low resolution image (b1) in Figure 2.

3. ERROR SOURCES

In practice the optical system is not ideal. The illumination beams from different illumination angles have non-identical and non-uniform intensities as well as wavefront aberrations. In the imaging system there also exist optical aberrations with the two Fourier lenses, which can be modeled in the pupil function. Moreover, image noise and detector misalignments are additional error sources which need to be taken into account. While aberrations in the imaging system and detector noise have been addressed already in the literature, we focus on the illumination system as error source for Fourier ptychography.

3.1 Illumination aberrations

For simplicity, we assume that there are only aberrations from the illumination system. The symbols for the sample object, the illumination, etc. are listed in Table 1.

Table 1: Complex amplitudes of the components in Figure 1

U_{illu}	ideal illumination
ΔU_{illu}	illumination aberration
U_{Obj}	sample object
P	ideal pupil function
U_{i}	image

By following [5], the frequency domain representation of the complete coherent imaging system illustrated in Figure 1 can be described in equation (1), which corresponds to equation (2) in the space domain.

$$\mathcal{F}\{U_{\mathrm{i}}\} = \mathcal{F}\left\{(U_{\mathrm{illu}} + \Delta U_{\mathrm{illu}}) \circ U_{\mathrm{Obj}}\right\} \cdot P \tag{1}$$

$$U_{\mathrm{i}} = \left[(U_{\mathrm{illu}} + \Delta U_{\mathrm{illu}}) \circ U_{\mathrm{Obj}}\right] * \mathcal{F}\{P\} \tag{2}$$

where $\circ$ denotes the Hadamard product and $*$ represents the two-dimensional convolution.

From equation (1) we can see that the Fourier transform of the part $\left[(U_{\mathrm{illu}} + \Delta U_{\mathrm{illu}}) \circ U_{\mathrm{Obj}}\right]$ can be different if the aberrations ΔU_{illu} of the illumination beams from different illumination angles are different. This leads to a non-consistency in the overlapping region from

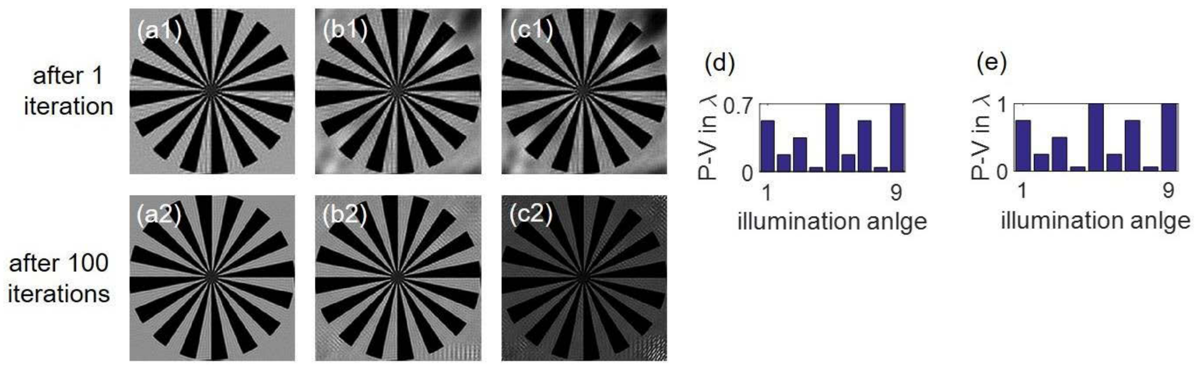

Figure 3: Influence of the spherical aberration from simulations. (a1) – (a2) Reconstructed images after 1 iteration and 100 iterations with no wavefront aberrations by using the FPM algorithms. (b1) – (b2) Reconstructed images after 1 iteration and 100 iterations with spherical aberration in the illumination system. The peak to valley distances of the spherical aberration on 9 fixed illumination angles vary between 0 and 0.7λ shown in (d). (c1) – (c2) Reconstructed images after 1 iteration and 100 iterations with spherical aberration in the illumination system. The peak to valley distances of the spherical aberration on 9 fixed illumination angles vary between 0 and 1λ shown in (e).

every two neighboring Fourier spectra and might cause the FPM algorithm failing in reconstructing the image.

3.2 Reconstructed intensity images

We choose the spherical aberration in the illuminating waves as an example, and investigate its influence on the quality of the reconstructed intensity images by using the FPM algorithm.

Figure 3 shows the reconstructed intensity images resulting from our simulation. Here we change the corresponding peak to valley aberration for 9 fixed illumination angles. The second column shows the results without aberrations. In the third column the peak to valley distance varies between 0 to 0.7 wavelength. In the fourth column the peak to valley distance varies between 0 to 1 wavelength. After 100 iterations, the results with a broader range of peak to valley aberrations are worse. This shows that the FPM algorithm is sensitive to the amount of spherical aberration in the illumination waves.

The experimental results shown in Figure 4 reconstructed with 9 low resolution intensity images confirm the aforementioned results. The spherical aberration of the illumination wavefronts on 9 fixed illumination angles in the second experiment has a wider range of the peak to valley aberrations than in the first experiment.

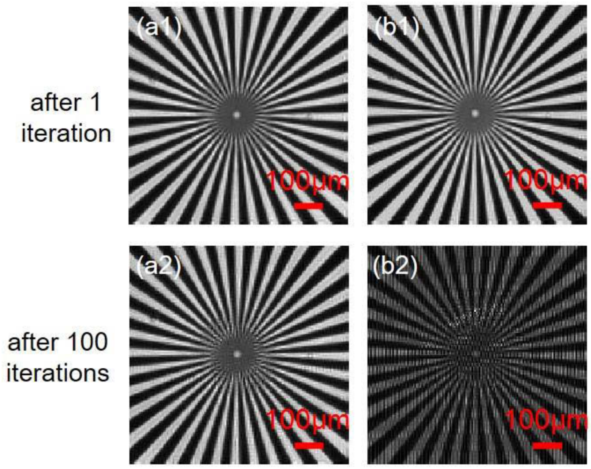

Figure 4: Influence of the spherical aberration: experimental results. (a1) – (a2) Reconstructed images after 1 iteration and 100 iterations with 9 measured low resolution images from the first experiment. (b1) – (b2) Reconstructed images after 1 iteration and 100 iterations with 9 measured low resolution images from the second experiment, where the spherical aberration is larger than in the first experiment.

4. REMOVAL OF THE ILLUMINATION ABERRATIONS

Illumination aberrations distort the quality of the reconstructed image when applying the FPM algorithm. Practically one can reduce the illumination aberrations by using more accurate and identical illumination devices. Such devices are often expensive and therefore the cost of using the FPM algorithm in real world applications will increase significantly. Therefore, we discuss a low cost solution, i.e., removing the illumination aberrations from the measured images by using a post-processing algorithm.

Again, we assume that only illumination aberrations exist in the whole optical system illustrated in Figure 1. From equation (2) we can see that the complex amplitude of the image is a nonlinear function of the illumination, the object, and the Fourier transform of the pupil function. The nonlinearity is caused by the concatenation of the Hadamard product and the convolution operation. In general it is difficult to express the aberrations U_{Obj} explicitly as a function of U_{i}, U_{illu}, ΔU_{illu}, and $\mathcal{F}(P)$.

A linear relationship is available in equation (1), which is the Fourier transform of (2). Moreover, if the size of the aperture stop is bigger than or equal to the size of the whole Fourier spectrum $\mathcal{F}\{(U_{\text{illu}} + \Delta U_{\text{illu}}) \circ U_{\text{Obj}}\}$, the pupil function P can be treated as a constant function, whose Fourier transform is the Dirac delta function. It is known that the convolution of a function and the delta function is still the original function if the delta function is centered at the origin. In this way, the convolution operation can be completely removed. That means, if we also take an additional intensity image of the illumination in the experiment, i.e., by taking away the object from the object plane, then we can construct both the complex amplitudes of $(U_{\text{illu}} + \Delta U_{\text{illu}}) \circ U_{\text{Obj}}$ and $(U_{\text{illu}} + \Delta U_{\text{illu}})$ with the measured intensity images by using the phase retrieval algorithm developed von Fienup [2] . In the end, the complex amplitude of the sample object can be calculated by element-wise dividing $(U_{\text{illu}} + \Delta U_{\text{illu}}) \circ U_{\text{Obj}}$ and $(U_{\text{illu}} + \Delta U_{\text{illu}})$. Thus (a part of) the sample object having a Fourier spectrum narrower than the aperture stop is reconstructed.

The FPM algorithm is applied in the situation that the sample object has a Fourier spectrum larger than the size of the aperture stop. Although it is still possible to apply the aforementioned method to get the complex amplitudes of $[(U_{\text{illu}} + \Delta U_{\text{illu}}) \circ U_{\text{Obj}}] * \mathcal{F}(P)$ and $(U_{\text{illu}} + \Delta U_{\text{illu}}) * \mathcal{F}(P)$, we cannot obtain the true complex amplitudes of $(U_{\text{illu}} + \Delta U_{\text{illu}}) \circ U_{\text{Obj}}$ and $(U_{\text{illu}} + \Delta U_{\text{illu}})$. This is because a deconvolution operation cannot solve equation (2) exactly. Therefore, it is not possible to remove the illumination aberrations perfectly by applying a post-processing method on the obtained images.

5. CONCLUSION AND DISCUSSION

The FPM algorithm can provide a high resolution image by stitching together the Fourier spectra of a number of individually measured low resolution intensity images using a phase retrieval algorithm. We show by numerical simulations and experiments that the optical aberrations of the illumination system distort the quality of the reconstructed intensity image. Applying the theory of Fourier optics, it is possible to remove the aberrations by using a post-processing method. However, this method is not suitable for the FPM algorithm because of the finite aperture size and the nonlinearity after convolution. In practice the post-processing method will fail to completely remove the aberration. In future it is interesting to study how much illumination aberrations can be removed by a numerical algorithm and under which condition it is worth using the numerical algorithm.

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