Enhanced edge extraction using spiral phase plate in optical scanning holography based on Gaussian beam apodization

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Abstract: Enhanced edge extraction with high resolution is demonstrated in optical scanning holography (OSH) system by manipulating the radius of the spiral phase plate (SPP) to dampen down the sidelobes of the point spread function.

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1. Introduction

In this paper, we propose a new method to increase the spiral phase plate (SPP) based edge enhancement by Gaussian beam apodization. The limited size of the Gaussian beam can be used to apodize the sidelobes of the PSF, which would lead to a high contrast edge enhancement with higher resolution.

OSH is a two-pupil optical system, in which the combined coherence beams from the two pupils are used for 2D heterodyne scan. The optical heterodyning and electronic multiplexing detection scheme make it intrinsically a twin-image-free holographic technique even the hologram itself is recorded on-axis [1]. OSH has already found various applications as microscopy [2], remote sensing [3], and image encryption etc [4]. To extract the edge information, people have used different methods such as aperture synthesis [5], or Laguerre Gaussian spatial filters [6]. In this manuscript, we will show that by using SPP as one of the pupil functions, and the other pupil a delta function, the edge information of the object can be extracted and recorded in the hologram.

2. The basic theory

The point spread function (PSF) of the imaging processing system is realized by applying Fourier transform on the spatial filter of the radial Hilbert transform, and it can be defined as [6]

$$h(r,\theta) = \frac{\pi R}{j2r}[H_0(x)J_1(x) - H_1(x)J_0(x)]\exp(j\theta), \tag{1}$$

where $x = 2\pi Rr/\lambda f$, λ is wavelength of laser, H_0 and H_1 are Struve functions of zero and first orders, and J_0 and J_1 are Bessel functions of zero and first orders.

One may notice from Eq. (1) that the PSF of SPP would change according to the radius R. Fig. 1 shows SPP with different radius R. From this figure, we can find that the radius of the mainlobe and sidelobes would increase gradually when the radius R is decreasing.

To generate vortex beam and extract edge information of the object in OSH, we set the pupil function $p_1(x,y)$ as the SPP, while keep $p_2(x,y) = \delta(x,y)$.And the generated OTF of the system can be expressed as

$$OTF_{SPP}(k_x,k_y;z) = \exp\left[-j\frac{z}{2k_0}(k_x^2+k_y^2)\right] \times p_1^*(\frac{-f}{k_0}k_x, \frac{-f}{k_0}k_y), \tag{2}$$

The analysis so far is based on the assumption that the output of the laser source is a true plane wave, and that $p_2(x,y)$ can be regarded as a true point source, which is impossible to realize. Since the spatial distribution of the laser beam is in general taken to be Gaussian, which can be expressed as

$$\widetilde{OTF}_{SPP}(k_x,k_y;z) = \frac{1}{\pi}\exp\left[-\frac{\sigma}{4\pi^2}(k_x^2+k_y^2)\right] \times p_1^*(\frac{-f}{k_0}k_x, \frac{-f}{k_0}k_y), \tag{3}$$

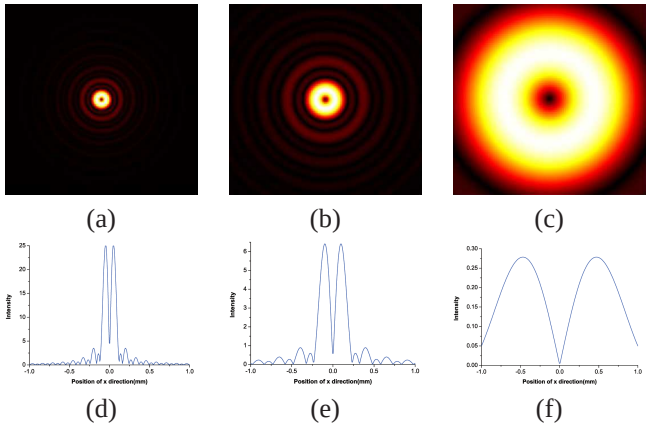

Fig. 1. SPP with different radius R. (a, d) for $R = 2.002\,\mathrm{mm}$, (b, e) for $R = 1.008\,\mathrm{mm}$, (c, f) for $R = 0.21\,\mathrm{mm}$; (a-c) are intensity distributions of the PSF, and (d-f) are intensity profiles in one radial section of the PSF.

where

$$\sigma = \eta\left(\frac{\lambda f}{\omega_s}\right)^2 + \eta\left(\frac{\pi\omega_p z}{f}\right)^2 + j\pi\lambda(1-2\eta)z, \eta \quad = \frac{\omega_s^2}{\omega_p^2+\omega_s^2}.$$

To check the result, for the ideal case of $v(x,y) = 1$ and $p_2(x,y) = \delta(x,y)$, letting $\omega_s \to \infty$ and $\omega_p \to 0$, one can deduce that $\eta \to 1$, $\sigma \to -j\pi\lambda z$, and Eq. (3) thus reduces to the same functional form as that of Eq. (2).

By compare Eq. (3) and Eq. (2), one can see that the intrinsic Gaussian beam performs like a Gaussian lowpass filter actually, which would lead to a PSF with limited size. The sidelobes located outside the limit of the PSF will be apodized for sure. This would lead to an edge extraction with better resolution as one can expected.

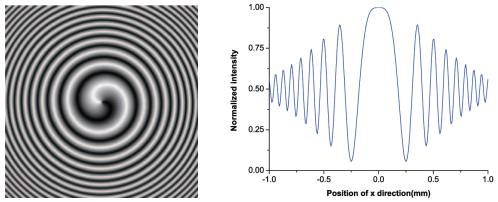

Fig. 2. (a) The generated vortex beam in OSH, and (b) the cross section for $y = 0$.

The generated PSF of the OSH system is shown in Fig. 2 (a), in which one can observe the detailed structure of the vortex beam. The cross section for $y = 0$ is shown in Fig. 2 (b). One can see that the fringe pattern is apodized by the appearance of the Gaussian envelope. The fringe visibility quickly drops after $|x| = 1\,\mathrm{mm}$, which is also the case for y-axis. This indicates that the Gaussian beam restricting the PSF to the size of $2\,\mathrm{mm} \times 2\,\mathrm{mm}$, and sidelobes located outside this range would be apodized.

3. Simulation and Analysis

Fig. 3 (a) shows the object used in our simulation. The extracted edge with the proposed method are shown in Figs. 3 (b) and (c), with $R = 2.002\,\mathrm{mm}$ and $R = 0.21\,\mathrm{mm}$, respectively. One can observe large improvement of the edge enhancement when the radius R of the SPP is decreasing.

We have also studied the relationship between the radius R of SPP and the resolution of the edge-enhancement, which is defined as the 3 dB bandwidth of the intensity distribution here. The result is shown in Fig. 4. One can see that if the the radius R decreases, the resolution increases almost linearly. The reason lies in the fact that the radius of the mainlobe as well as sidelobes increase when R decreases, which would result in less sidelobes into the FZP of the

(a) (b) (c)

Fig. 3. (a) The object as well as the extracted edge in case of (b) $R = 2.002$ mm, and (c) $R = 0.21$ mm.

OSH system. As we expected, the resolution would be better when decreasing the radius R. The resolution approaches maximum at around 0.18 mm, where the sidelobes are almost fully suppressed. However, if one decreases the radius R further into the range below 0.18 mm, the resolution would decrease. This is due to the reason that part of the mainlobe has also been apodized in this case, which degrades the resolution to some extent.

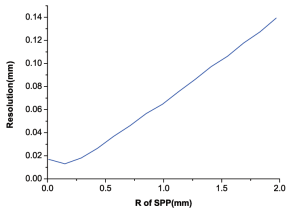

Fig. 4. The relationship between the radius R of SPP and the resolution of the edge-enhancement.

4. Conclusion

In conclusion, we presented an edge extraction method based on SPP in OSH system. Edge information of the object is extracted by applying the radial Hilbert transform. The high resolution is achieved due to the intrinsic Gaussian distribution of the laser output, which results in a PSF of the system with finite size. By manipulating the radius of SPP, the sidelobes locating beyond the limited size could be apodized. We have shown that an enhanced edge extraction with high resolution can be achieved by the proposed method.

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