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Algorithm of far-field centre estimation based on phase-only matched filter*

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Estimation of the far-field centre is carried out in beam auto-alignment. In this paper, the features of the far-field of a square beam are presented. Based on these features, a phase-only matched filter is designed, and the algorithm of centre estimation is developed. Using the simulated images with different kinds of noise and the 40 test images that are taken in sequence, the accuracy of this algorithm is estimated. Results show that the error is no more than one pixel for simulated noise images with a 99% probability, and the stability is restricted within one pixel for test images. Using the improved algorithm, the consumed time is reduced to 0.049 s.

Keywords: beam auto-alignment, far-field, image process, phase-only matched filter
PACC: 4280, 4230K, 4230V

1. Introduction

With the development of laser systems used for the study of inertial confinement fusion, the structure of the systems becomes more complicated, and the number of optical elements is larger. Auto-alignment system based on image processing is used to adjust beam pointing and centring before every fire.[1−4] Far-field centre estimation is a key technology of this system. It determines the accuracy of the beam pointing. The centroid method and the edge detection have been used for centre estimation already.[5] Because of defocus and interference effects, we cannot obtain satisfactory results by using them. A phase-only matched filter (POF) can overcome these problems by using a suitable template. For searching this template, we analyse the features of a square beam used in this system. According to the template, we describe the algorithm of centre estimation by using the POF, and estimate the accuracy and the stability of this algorithm by using simulated images and test images separately.

2. Features of beam far-field

In order to use the POF for effectively conducting the centre estimation, we need an appropriate template. To search for it, we must know the features of the beam far-field. The principle of Fourier optics may be used to analyse the square beam.

We assume that a monochromatic plane wave with an amplitude of a uniformly irradiates a plane located at a distance of d from the lens L. Its amplitude transmittance $t_A(x, y)$ is defined as

$$t_A(x,y) = \begin{cases} 1 & |x| < b, |y| < b, \\ 0 & |x| > b, |y| > b, \end{cases} \tag{1}$$

where b is half the size of the square aperture of the plane as shown in Fig.1, and the aperture of this plane is much smaller than that of the lens.

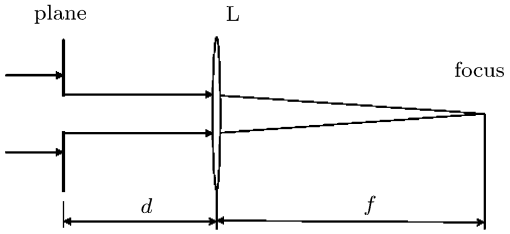


Fig.1. Simple optical focus system for square beam.

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In addition, let $F_0(f_x,\ f_y)$ represent the Fourier spectrum of light transmitted by the plane, and also let $U_f(u,\ v)$ denote the amplitude distribution in the back focal plane of lens, that is

$$F_0(f_x,\ f_y) = F\{At_A\}, \tag{2}$$

$$U_f(u,\ v) = \frac{\exp\left[\mathrm{j}\frac{k}{2f}\left(1-\frac{d}{f}\right)(u^2+v^2)\right]}{\mathrm{j}\lambda f} \times F_0\left(\frac{u}{\lambda f},\ \frac{v}{\lambda f}\right), \tag{3}$$

where λ is the wavelength of monochromatic plane wave, and f is the focal length of lens. Substituting expression (2) into expression (3) yields

$$U_f(u,\ v) = \frac{A\exp\left[\mathrm{j}\frac{k}{2f}\left(1-\frac{d}{f}\right)(u^2+v^2)\right]}{\mathrm{j}\lambda f} \times \int\int_{-\infty}^{+\infty} t_A(x,\ y) \times \exp\left[-\mathrm{j}\frac{2\pi}{\lambda f}(xu+yv)\right]\mathrm{d}x\mathrm{d}y. \tag{4}$$

The intensity across the focal plane is[6]

$$I_{\mathrm{f}}(u,\ v) = \frac{A^2}{\lambda^2 f^2}\left|\int\int_{-\infty}^{+\infty} t_A(x,\ y)\exp\left[-\mathrm{j}\frac{2\pi}{\lambda f}(xu+yv)\right]\mathrm{d}x\mathrm{d}y\right|^2. \tag{5}$$

Because of the wave front distortion and some other noises, such as interference，stray light and so on, the intensity distribution across the focal plane is slightly distorted as shown in Fig.2. Fortunately, the features of the focus remain there, and the algorithm in which the ideal intensity distribution is used as the template of POF is a powerful method.

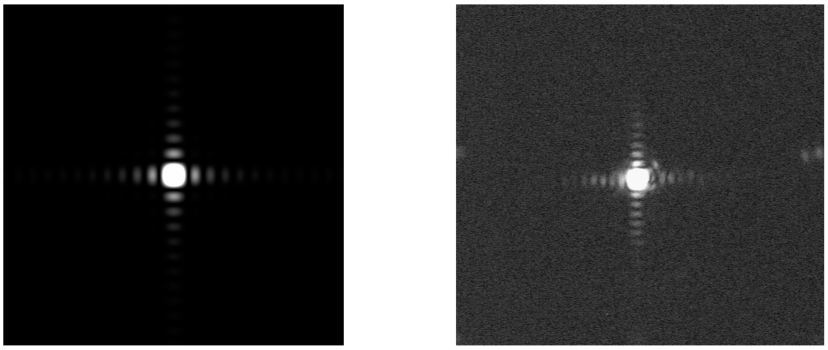


Fig.2. Far-field images of beam, where (a) shows the simulated far-field image and (b) exhibits the test far-field image.

3. Algorithm descriptions

In this section, the principle of POF is presented first. And then the algorithm of POF is applied to the centre estimation. A classical matched filter (CMF) is done well with pattern recognition. Gradually, one finds that the information about phase is more important than that about amplitude, thereby the POF is developed.[7−9]

Assume that $s(x,y)$ and $t(x,y)$ represent intensity distributions across the focal plane and the template respectively. When using the matched filter to detect the position of focus, we need to make a correlation of $s(x,y)$ and $t(x,y)$. We know that making a correlation of $s(x,y)$ and $t(x,y)$ is equivalent to performing the convolution of $s(x,y)$ and $t(-x,-y)$, and the convolution operator in the space domain is equivalent to the product operator in the frequency domain. Let

$$S(u,v) = A_{\mathrm{S}}(u,v)\exp\left[\mathrm{i}\Phi_{\mathrm{S}}(u,v)\right], \tag{6}$$

and

$$T(u,v) = A_{\mathrm{T}}(u,v)\exp\left[\mathrm{i}\Phi_{\mathrm{T}}(u,v)\right] \tag{7}$$

represent the Fourier transforms of intensity distributions across the focal plane and the template $s(x,y)$ and $t(x,y)$ respectively, where Φ is phase distribution,

and

$$T_{\mathrm{C}}(u,v) = A_{\mathrm{T}}(u,v)\exp\left[-\mathrm{i}\Phi_{\mathrm{T}}(u,v)\right] \tag{8}$$

denotes the template of CMF in frequency domain. We are interested just in phase distribution of the template for POF, therefore, the amplitude of template $A_{\mathrm{T}}(u,v)$ is set to be unity, and the template is changed into[10,11]

$$\begin{aligned} T_{\mathrm{P}}(u,v) =& T_{\mathrm{C}}(u,v)\cdot\left|T_{\mathrm{C}}(u,v)\right|^{-1} \\ =& \exp\left[-\mathrm{i}\Phi_{\mathrm{T}}(u,v)\right]. \end{aligned} \tag{9}$$

The correlation between target and template is denoted as

$$P(\varepsilon,\eta) = F^{-1}\left\{S(u,v)\cdot T_{\mathrm{P}}(u,v)\right\}, \tag{10}$$

and the position of correlation peak for POF is

$$\begin{aligned} (x_{\mathrm{cp}}, y_{\mathrm{cp}}) =& \{(x,y)\,|P(x,y) \\ =& \max\left[P(\varepsilon,\eta)\right]\}. \end{aligned} \tag{11}$$

Given the position of correlation peak, the relative position of focus centre is known. If we know the original position of focus in the template, we can calculate its absolute position in the image, which we need. So, the absolute position of the focus is defined as

$$\begin{aligned} x_{\mathrm{ap}} &= x_{\mathrm{cp}} + x_{\mathrm{t}}, \\ y_{\mathrm{ap}} &= y_{\mathrm{cp}} + y_{\mathrm{t}}, \end{aligned} \tag{12}$$

where $(x_{\mathrm{ap}},\ y_{\mathrm{ap}})$, $(x_{\mathrm{cp}},\ y_{\mathrm{cp}})$ and $(x_{\mathrm{t}},\ y_{\mathrm{t}})$ are the coordinates of the focus, which we need, correlation peak, and focus in the template respectively. That is the very algorithm of centre estimation, and then we should evaluate this algorithm.

4. Algorithm evaluations

Because the exact position of centre of test focus is unknown, we use the simulated far-field images for evaluation first. Some noises are added into simulated images to evaluate the accuracy and stability. Then, we evaluate the stability of this algorithm by using the test far-field images. First, a comparison is made between the simulated images without noise, obtained by using the CMF and the POF separately. The peak of correlation image obtained by using the POF is sharper than that by using CMF as shown in Fig.3, and the peak position estimation is much easier and more accurate. This can be explained by the definition of POF. Since the function $|T_{\mathrm{C}}(u,v)|^{-1}$ in Eq.(9) acts as a high-pass filter for the objects we are dealing with, the POF is expected to have high-pass filter features, and there is a favourable low frequency suppression that enhances the correlation peak.

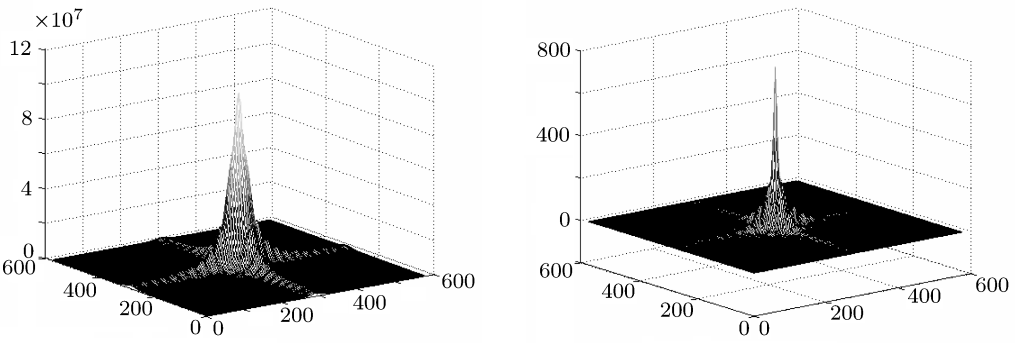


Fig.3. Correlation peaks in images obtained by using the CMF (a) and the POF (b) separately.

For evaluating the accuracy and the stability of this algorithm, we use the simulated far-field images with added noises to simulate different circumstances, with the positions of focus centres exactly known. In order to simulate the noises caused by stray light and the charge coupled device (CCD), the Gaussian noises with different root mean squares (RMSs) and mean values are added into the images. Figure 4 shows the simulated far-field image with a Gaussian noise at a mean value of 100 and an RMS of 1000, and Fig.5 shows the peak in Fig.4 obtained by using the POF.

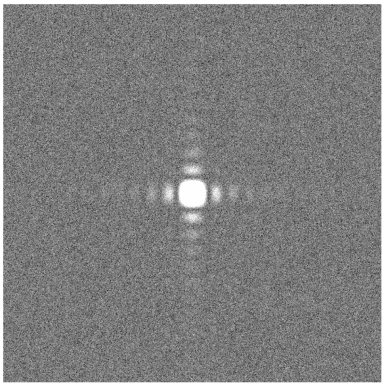


Fig.4. Gaussian noise with a mean value of 100 and an RMS of 1000.

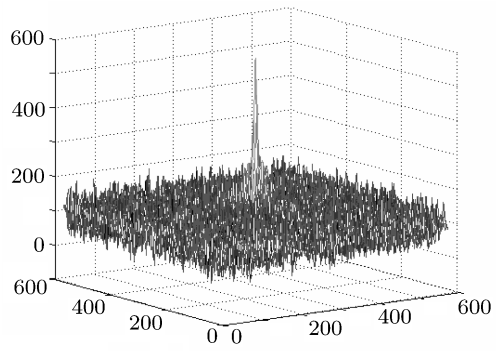


Fig.5. Peak in Fig.4 obtained by using POF.

Figure 6 shows the results of position estimation from the far-field images with different Gaussian noises. The results indicate that the position estimated by using the POF is not sensitive to Gaussian noise. A large number of experiments indicate that even the mean value is increased up to 110 or the RMS is enhanced up to 10000, the jitter is only one pixel for the simulated noise images with a 99% probability. This feature can help us eliminate the noise caused by the stray light and the CCD, which cannot be overcome by traditional methods very well.

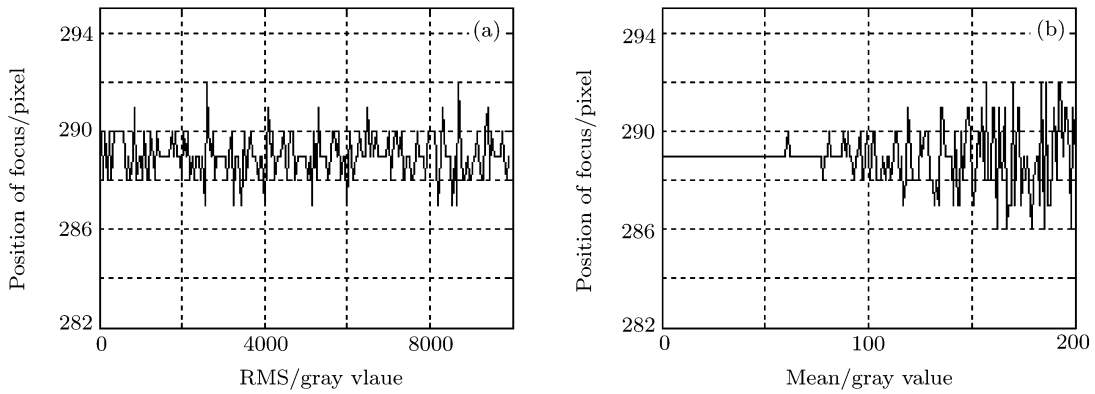


Fig.6. Position estimations for different noises, where (a) shows the estimation for different RMSs at a mean value of 100, and (b) indicates the estimation for different mean values at an RMS of 1000.

For simulating the influence of interference noise, periodic noise is added into the simulated images. We use two kinds of periodic noises to simulate the two kinds of common interference patterns, one is of parallel stripes and the other is of concentric annuluses, both of which are sine distribution with an amplitude of A and a frequency of f as shown in Fig.7.

Figure 8(a) reveals that an uncertainty is only one pixel for images with parallel stripe noise (Fig.7(a)). For these images with concentric annulus noise (Fig.7(b)), the largest error is 2 pixels, but the probability is less than 1% as shown in Fig.8(b). We find that if the mean value of the noise of this kind is too big, say, more than 120, the results would be uncertain.

Now, we can c conclude that the accuracy and the stability of POF are very good, and the error is no more than one pixel with a 99% probability for the simulated images. In a test system, we seldom meet the noise with large amplitudes, for example, $A > 100$. Because the exact position of focus centre in a test image is unknown, we are interested just in the stability of this algorithm for the test focal images. Next, we use the test images for estimating.

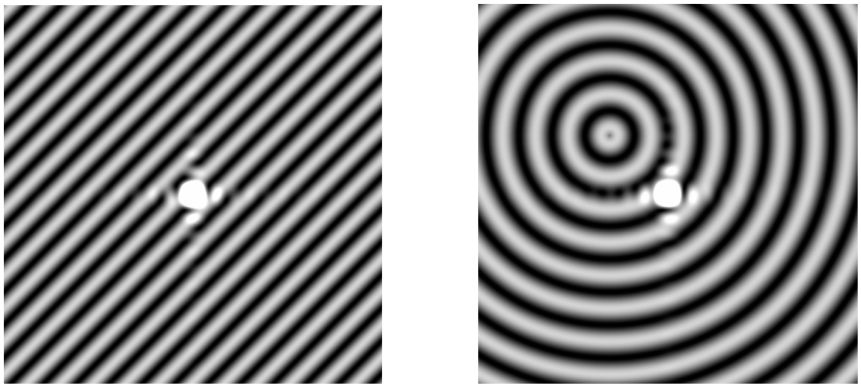


Fig.7. Focal images with interference noises, where (a) shows the image with parallel stripe noise at f=0.02 and A=100 and (b) indicates the image with concentric annulus noise at f=0.02 and A=100.

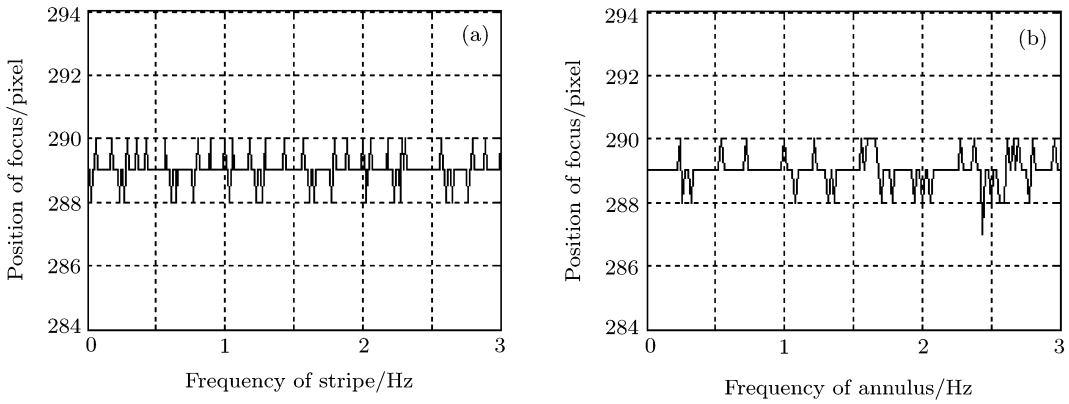


Fig.8. Position estimations for interference noises parallel stripe noise (a), and concentric annulus noise (b).

There are used 40 images in total, which are taken in sequence, in the evaluation of the stability of this algorithm. In order to reduce the uncertainty causing by optical drift, we use a simple optical system with a short optical path for taking the images. Figure 9 shows one of the far-field images, and Fig.10 indicates that the uncertainty within only one pixel. The x-axis of focal position is shown only in Fig.10, and the uncertainty of y-axis is also restricted within only one pixel.

Considering that the auto-alignment system needs a shorter adjusting time, we optimize the algorithm. For this algorithm, most of the time is spent on the fast Fourier transform (FFT), and the consumed time is known to be related to the size of image. As a matter of fact, only a small area of the image including the focus is useful. So, we choose this part by preprocessing, record the initial position of this part, and only use it for position estimation. The coordinate value we need is obtained, with the initial position of this area known. With this method, the consumed time is reduced from 0.211 to 0.049 s.

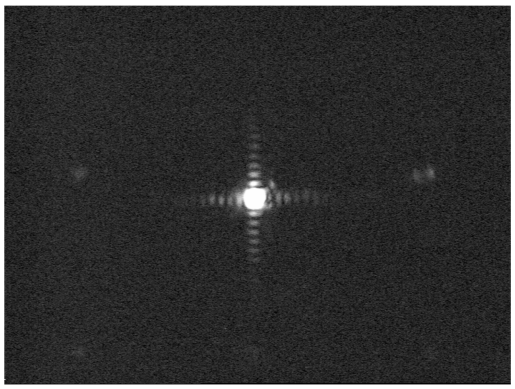


Fig.9. Test far-field image.

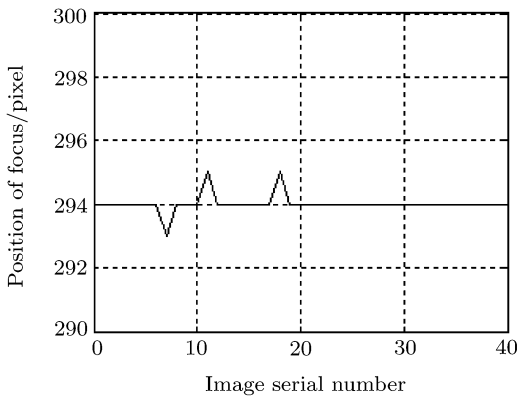


Fig.10. Uncertainty of the position estimation.

5. Conclusions

Based on the principle of Fourier optics, the features of far field of square beam are analysed, and a POF is applied to the algorithm of centre estimation. Then three kinds of noise models are used for simulating three kinds of common noises. The results indicate that the error is no more than one pixel for all of them with a 99% probability. Following that, 40 test images taken in sequence are processed, and the obtained result shows that the estimated position uncertainty is restricted within only one pixel. In the end, the algorithm is improved, and the consumed time is reduced from 0.211 to 0.049 s.

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