The application of wavefront coding in the infrared optical system in the tokomak fusion reaction

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A R T I C L E   I N F O

Article history:
Received 7 November 2011
Received in revised form 8 March 2012
Accepted 8 March 2012
Available online 1 April 2012

Keywords:
Wavefront coding
Nuclear fusion
Tokomak
Infrared ray (IR) optical system

A B S T R A C T

This article describes the principle of wavefront coding (WFC) technology and the role it plays in optical system. The infrared optical system in tokomak includes three parts: (1) the combination of the concave aspheric mirror and flat mirror; (2) the Cassegrain system; (3) the relay group lenses. Because of the application of wavefront coding, the optical system is less sensitive to the change of the temperature and the depth of field is enlarged. Comparing the modulation transfer function (MTF) of the original optical system and the improved system in different temperatures, the results show that the new system can be used in a larger range of temperature.

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1. Introduction

Wavefront coding was first proposed by Cathey and Dowski to expand the depth of field. It makes a blurred image by coding the wavefront at the aperture or exit pupil of the optical system. Then the digital image processing system decodes this blurred image in order to get a final clear image [1]. Because of the application of wavefront coding, the optical system is not sensitive to the defocus. The optical transfer function (OTF) or the point spread function (PSF) is not sensitive to the defocus either. In the range of cutoff frequency, there is no zero in the modulation transfer function (MTF) which means the information is not lost. Thus the blurred images of different defocus can be inverse filtered or deconvoluted to get clear images. The significant advantage of this optical system is that the depth of field can be extended without reducing the pupil. In addition to expanding the depth of field, wavefront coding system can also inhibit some aberrations, just like spherical, field curvature and dispersive [2,3], which are caused by defocus. Tokomak was first proposed by Soviet scientists. And in the fifty years, as the application of superconductivity, tokomak made great progress. Until now, tokomak is being studied in many countries: The tokomak fusion test reactor (TFTR); the thermonuclear experimental reactor (ITER). There is also tokomak in China, such as the HT-7, built in 1995, and the experimental advanced super conduction tokomak (EAST) [4–6].

In tokomak, because of the particular working condition, such as ultra-high temperature and ultra-high pressure, the temperature of the components facing the vacuum chamber and the state of the atoms have to be observed in real time in order to protect the fusion reaction. The IR thermography diagnostic equipment is playing an important role in this respect. Because the range of the working temperature is great, the image quality deteriorates when temperature changes. The WFC can improve this situation.

2. The theory of wavefront coding

The impact on optical system by geometric aberrations can be regarded as the impact on the system by wavefront aberration. The imaging quality of the system can be described by the relation of generalized pupil function \( P(\xi, \eta) \) and wavefront aberration \( W(\xi, \eta) \). In the case of two-dimensional, the generalized pupil function is [7]

\[
P(\xi, \eta) = P_d(\xi, \eta) \exp[jkW(\xi, \eta)]
\]

where \( \xi \) is the normalized spatial coordinates, \( P_d(\xi) \) is the pupil function of the diffraction-limited optical system, \( k \) is the wave number and \( W \) is the wavefront function. The function of wavefront
function and defocus which can be get by the theory of canonical coordinates developed by Prof. H.H. Hopkins is [8]

\[
\psi = \frac{\pi D^2}{4\lambda} \left( \frac{1}{f} - \frac{1}{d_0} - \frac{1}{d_f} \right) = \frac{2\pi}{\lambda} W = kW 
\] (2)

When an additional phase is add on the pupil of the optical system, the \( P_d(\epsilon) \) is

\[
P_d(\epsilon) = \left\{ \begin{array}{ll}
\frac{1}{\sqrt{2}} \exp[j\theta(\epsilon)], & \text{in pupil} \\
0, & \text{out of pupil}
\end{array} \right.
\] (3)

The additional phase is

\[
\theta(\epsilon) = \alpha \epsilon^2, \quad (\alpha \neq 0, \gamma \neq \{0, 1\})
\] (4)

Considering Eqs. (3), (2) and (1) and the optical transfer function is the self-correlation of the pupil function. The optical transfer function is

\[
H(u, \psi) = \int P (\epsilon + \frac{u}{2}) : P^* (\epsilon - \frac{u}{2}) d\epsilon 
\] (5)

Considering the Ambiguity Function and the above equations, the following conclusion can be get: when the additional phase \( \theta(\epsilon) \) equal to \( \alpha \epsilon^3 \), there is no defocus in MTF which indicates MTF is no longer affected by defocus. There is only a quadratic relationship between PTF and defocus that demonstrates the position of PTF shifts when defocus shifts. The effect of PTF can be reduced by changing \( \alpha \). This impact can be ignored when \( \alpha \) takes value between 20\( \pi \) and 80\( \pi \). The OTF is

\[
H(u, \psi) \approx \left. \left( \frac{\pi}{12|\alpha|} \right) \exp(j\frac{\alpha \epsilon^3}{4}) \right|, 
\] (6)

\( u \neq 0, \quad \exists \alpha \in [20,80] \)

This article studies wavefront coding in the form of three phase plate, \( \theta(\epsilon) = \alpha \epsilon^3 \).

3. The optical system

The range of the working wavelength of the system in this paper is from 8 \( \mu \)m to 13 \( \mu \)m. The system consists of three parts [9]: (1) aspheric concave mirror and a plane mirror (Fig. 1). There is a small hole in the plane mirror. The aspheric concave mirror is behind the plane mirror. The combination of the aspheric concave mirror and the plane mirror makes the angle of the beam deviate from the original optical axis. The emergent ray from these two mirrors is collimated into the Cassegrain system. (2) Cassegrain system (Fig. 2). (3) The relay group lenses (Fig. 3). The whole optical system is shown in Fig. 4.

The scene temperature range of this system is from \(-15^\circ C\) to 200\( ^\circ C \). As is shown in Fig. 5, a little change in temperature may cause a noticeable image quality decline (Fig. 5). Something needed to be done to compensate for the decline in image quality. Although the image can maintain in good quality, the workload is larger in the meantime. The good image quality can be maintained without increasing workload by bringing in wavefront coding. The wavefront coding in this paper is placed at the aperture.
The binary optic 1 is one of forms of wavefront coding. Binary optic can transform the wavefront. The binary optic 1 in ZEMAX is chosen as the form of wavefront coding in this paper. The equation of the binary optic 1 is as following:

$$\phi = \sum_{i=1}^{N} A_i E_i(x, y)$$  \hspace{1cm} (7)

When $N$ is equal to 9, the equation is:

$$\phi = A_1 x + A_2 y + A_3 x^2 + A_4 xy + A_5 y^2 + A_6 x^3 + A_7 x^2 y + A_8 xy^2 + A_9 y^3$$  \hspace{1cm} (8)

When $A_6$ and $A_9$ are equal to 62.8, the results of design are as follows. Fig. 6 shows the spot diagram which is the geometrical characteristic of optical system with wavefront coding. Fig. 7 is the wavefront map. Fig. 8 is the MTF of different fields. As for different temperatures, the MTF is shown in Fig. 9.

As can be seen from above figures, the infrared optical system with wavefront coding is not sensitive to the change of
temperature. Although the image quality declines, it can be inverse filtered or deconvoluted to get clear images by image processor.

4. Conclusion

A wide-angle infrared thermography diagnostic using reflective optics has been designed. Because of the large dynamic range of temperature, some measures have been taken in order to prevent the image quality from decreasing. By bringing in wavefront coding, the good image quality can be maintained without increasing workload.

References