Optics Communications 407 (2018) 311–320

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Volume moiré tomography based on projection extraction by spatial phase shifting of double crossed gratings

Jia Wang [a], Zhenyan Guo [b,*], Yang Song [c], Jun Han [a]

[a] School of Optical and Electronic Engineering, Xi'an Technological University, Xi'an 710021, China
[b] School of Electronic and Optical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China
[c] Department of Information Physics and Engineering, Nanjing University of Science and Technology, Nanjing 210094, China

ARTICLE INFO

Keywords:
Phase shift
Phase retrieval
Moiré deflectometry
Tomographic image processing

ABSTRACT

To realize volume moiré tomography (VMT) for the real three-dimensional (3D) diagnosis of combustion fields, according to 3D filtered back projection (FBP) reconstruction algorithm, the radial derivatives of the projected phase should be measured firstly. In this paper, a simple spatial phase-shifting moiré deflectometry with double cross gratings is presented to measure the radial first-order derivative of the projected phase. Based on scalar diffraction theory, the explicit analytical intensity distributions of moiré patterns on different diffracted orders are derived, and the spatial shifting characteristics are analyzed. The results indicate that the first-order derivatives of the projected phase in two mutually perpendicular directions are involved in moiré patterns, which can be combined to compute the radial first-order derivative. And multiple spatial phase-shifted moiré patterns can be simultaneously obtained; the phase-shifted values are determined by the parameters of the system. A four-step phase-shifting algorithm is proposed for phase extraction, and its accuracy is proved by numerical simulations. Finally, the moiré deflectometry is used to measure the radial first-order derivative of projected phase of a propane flame with plane incident wave, and the 3D temperature distribution is reconstructed.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

Optical computerized tomography (OCT) is an effective and widely used technique for the diagnoses of flow fields with advantages of real-time, non-contact as well as high temporal and spatial resolutions [1]. It has been considered a powerful tool for 3D quantitative diagnoses of flow fields, such as the combustion profile by emission and chemiluminescence tomography [2,3], the temperature distribution by interferometric tomography [4], the refractive index distribution of supersonic wind tunnel [5], and the density distribution of supersonic jets by shadowing casting method [6]. Among several OCT techniques, one applying moiré deflectometry to measure the projected phase information is called moiré tomography [7,8]. Because of the higher anti-disturbing capability and wider measurement range comparing with various interference tomography techniques, it has been deeply explored and widely applied for the diagnoses of complex flow fields in harsh environments [9–11].

In moiré tomography, the refractive index distribution is initially measured, and according to the relationship of physical parameters and refractive index, the key characteristics of the flow fields are diagnosed [8,9,12]. The implementation of moiré tomography consists of three critical steps: (1) designs of multi-directional moiré deflectometry system for the measurements of projected phase information (which is introduced by varied refractive index along ray path) and corresponding algorithms for phase extraction; (2) tomographic reconstruction of refractive index by various algorithms (such as filtered back projection algorithm, algebraic reconstruction technique and so on); (3) inversion and diagnoses of physical parameters.

However, most of the existing moiré tomography techniques are mathematically based on 2D Radon Transform. It means that tested field should be split into several parallel slices and the deflected rays are limited in the planes, and each slice is independently reconstructed by 2D CT reconstruction. In order to present the 3D distribution of the object, the slices must be exactly stacked one by one. It is obvious that the traditional reconstruction is an approximation of the real field. On the contrary, volume moiré tomography (VMT), whose mathematical foundation is real 3D tomography theory, can maintain the relevance of the whole 3D field and achieve the real and accurate reconstruction [13]. It will be quite effective and more precise in studying the spatial characteristics of the tested flow fields. 3D filtered back projection

---

[*] Corresponding author.
E-mail address: guozy15@njust.edu.cn (Z. Guo).

http://dx.doi.org/10.1016/j.optcom.2017.09.029
Received 10 August 2017; Received in revised form 5 September 2017; Accepted 7 September 2017
Available online 5 October 2017
0030-4018/© 2017 Elsevier B.V. All rights reserved.

(FBP) based on 3D Radon Transform is an important algorithm for 3D tomographic reconstruction [14], which will be described in Section 2. According to 3D FBP algorithm, the radial second-order or first-order derivative of the projected phase should be measured firstly by moiré deflectometry.

Shearing interferometers by using double circular gratings or cross gratings have been studied for measuring the radial first-order derivative of the projected phase [13,15]. In our previous work, the radial shearing interferometer with double circular gratings has been studied [16,17]. As the spectra of different diffracted orders are overlapped in a series of concentric circles, it is not easy for filtering and imaging. Besides, as the distribution of moiré fringes is radial, large errors will arise in phase extraction of the center area. Nan Sun studied the shearing interferometer with double cross gratings and it is used to realize VMT to measure the 3D temperature distribution of a flame [13]. The diffraction spectra of the cross gratings are completely separated in space, which is convenient for spatial filtering and imaging. And the grid-like moiré pattern is the interaction of moiré fringes in two orthogonal directions. The traditional Fourier transform method was used for phase information retrieval, but to avoid the overlap of the Fourier transform spectrum, the system can only be used to measure small varied flames with dense moiré patterns, which limits the measurement range of VMT.

Phase extraction is a significant step for the implementation of VMT, which affects the accuracy of the tomographic reconstruction and measuring range. Many approaches have been studied, such as fringe detection methods [18], Fourier transform techniques [19] and phase-shifting methods [20]. Among those, spatial phase-shifting techniques are especially useful for rapidly varying flow fields, because they can generate several phase-shifted interferograms simultaneously. Generally, gratings play an important role in the spatial phase-shifted optical configurations. M. Kujawinska studied that phase shifting could be introduced by both lateral and longitudinal moving of gratings [21]. Then they used a linear grating to divide the probe light into three beams; polarization optical devices were then applied to obtain appropriate phase-shifted interferograms [22]. Kwon first introduced the diffraction phenomenon of a linear grating to produce diffraction orders, which can create the desired phase shifting [23]. Crossed gratings can be used to produce projection information or split light in two orthogonal directions. Quiroga used crossed gratings to produce projection information in two directions and extracted the phase information by Fourier transform [19]. Toto-Arellano placed a crossed grating in the spectra of the 4f system to generate several patterns and used polarization elements to generate phase shifting [24]. Based on the diffraction effect of gratings, three linear gratings [25] or a cross grating with a linear grating [26] can realize multiple-step spatial phase shifting in moiré patterns for the measurement of the partially first-order derivative of projected phase. The existing studies on the intensity distributions of moiré patterns generated by double cross gratings indicated that there are stable spatial phase shifts between horizontal and vertical moiré fringes of different spectra [13]. It means that spatial phase shifting methods can be used to extract the projected phase information contained in the moiré fringes.

The purpose of this paper is to realize VMT by a spatial phase-shifting moiré deflectometry with double cross gratings. In Section 2, the theory of 3D Radon Transform and 3D filtered back projection algorithm for refractive index reconstruction are presented. In Section 3, a simple spatial phase shifting moiré deflectometry with double cross gratings is presented and analyzed based on scalar diffraction theory, the explicit intensity distributions of moiré patterns on different diffracted orders are derived and the spatial phase shifting characteristics are studied. In Section 4, a four-step phase extraction algorithm is proposed, and the feasibility and accuracy are checked by numerical simulations. In Section 5, the system is used for reconstructing the 3D temperature distribution of a propane flame. Section 6 is the conclusion of this paper.

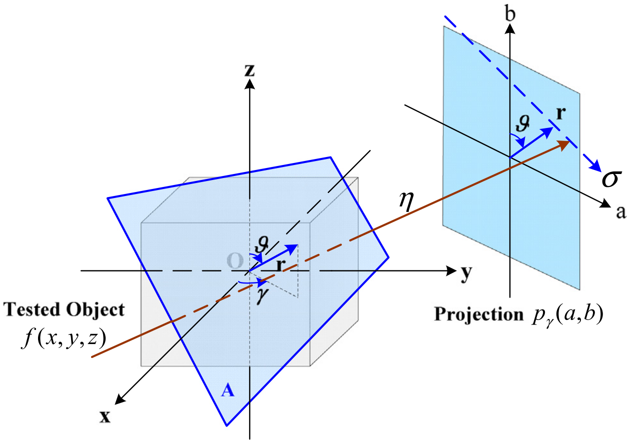

Fig. 1. Coordinate systems for 3D Radon Transform.

2. Principle of 3D computerized tomography

The mathematical foundation of VMT is 3D Radon Transform based on parallel projection. The coordinate systems for 3D Radon Transform are shown in Fig. 1. In 3D Radon Transform, the projection value is a surface integral of the parameters in tested field [14]. The projection direction is determined by azimuth angle γ and zenith angle ϑ. The integral surface A can be unambiguously determined by the vector $\mathbf{r}$, where the surface is perpendicular to $\mathbf{r}$ and has a distance of r to the origin

$$\mathbf{r} = \begin{pmatrix} r\cos(\gamma)\sin(\vartheta) \\ r\sin(\gamma)\sin(\vartheta) \\ r\cos(\vartheta) \end{pmatrix} \tag{1}$$

In mathematics, 3D Radon Transform can be expressed as

$$p_{\gamma,\vartheta}(r) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y,z)\,\delta(x\cos(\gamma)\sin(\vartheta) + y\sin(\gamma)\sin(\vartheta) + z\cos(\vartheta) - r)\,dx\,dy\,dz \tag{2}$$

where $f(x,y,z)$ is the function of tested object.

The 3D filtered back projection for tomography reconstruction [14], which can be derived by mathematical analysis from Eq. (2), is expressed as

$$f(x,y,z) = \frac{1}{2}\int_{\vartheta=0}^{\pi}\int_{\gamma=0}^{2\pi}\left\{\int_{\xi=-\infty}^{\infty} P_{\gamma,\vartheta}(\xi)\cdot e^{2\pi i\xi r}\xi^2\,d\xi\right\}\sin(\vartheta)\,d\gamma\,d\vartheta \tag{3}$$

where ξ^2 is a filter in frequency domain to the Fourier transform $P_{\gamma,\vartheta}(\xi)$ of $p_{\gamma,\vartheta}(r)$. By employing the differential properties of Fourier transform, the reconstruction formula can be reduced as

$$f(x,y,z) = -\frac{1}{8\pi^2}\int_{\vartheta=0}^{\pi}\int_{\gamma=0}^{2\pi}\left\{\frac{\partial^2 p_{\gamma,\vartheta}(r)}{\partial r^2}\right\}\sin(\vartheta)\,d\gamma\,d\vartheta \tag{4}$$

The flow fields are generally regarded as phase fields by ignoring the absorption. The object function $f(x,y,z) = n(x,y,z) - n_0$, where n_0 is the reference refractive index of the surrounding air, $n(x,y,z)$ is the refractive index of the phase field and must be equal to n_0 beyond a certain area.

The projection originally recorded by experiment is 2D integral of optical path difference along ray path when the parallel beam passes through the phase object, which is denoted as $p_\gamma(a,b)$. The azimuth angle γ determines the projection direction η and (a,b) is the coordinate of projected 2D images. In order to obtain the 3D Radon Transform value, a secondary integral should be utilized along σ, which

Download English Version:

https://daneshyari.com/en/article/5448972

Download Persian Version:

https://daneshyari.com/article/5448972

Daneshyari.com