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Multi-scale approach for analyzing convective heat transfer flow in background-oriented Schlieren technique

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ABSTRACT

The paper introduces a multi-scale processing method for quantitative study and visualization of convective heat transfer using diffractive optical element based background-oriented schlieren technique. The method relies on robust estimation of phase encoded in the fringe pattern using windowed Fourier transform and subsequent multi-scale characterization of the obtained phase using continuous wavelet transform. As the phase is directly mapped to the refractive index fluctuations caused by the temperature gradients, the multi-scale inspection provides interesting insights about the underlying heat flow phenomenon. The performance of the proposed method is demonstrated for quantitative flow visualization.

1. Introduction

For flow visualization, optical methods constitute an important class of measurement techniques because of non-invasive operation, full-field measurement and capability to provide both qualitative and quantitative insights with good sensitivity [1,2]. Some of the prominent optical techniques for flow visualization are outlined in [3]. Among these, beam deflection approach based on background distortion [4] is relatively popular for flow visualization because of relative ease of operation, digital data processing, cost-effective design and robustness against external disturbances. The applicability of this technique is further expanded by the enormous advances made in the field of computer hardware and software. This technique relies on mapping the refractive index variation to the distortions experienced by a background pattern. Background distortion techniques include background oriented schlieren (BOS) [5,6] and its variants [7], and synthetic schlieren technique [8]. Over the years, similar methods based on grid pattern distortions have also been proposed [9,10]. Most of these techniques are improvements over the schlieren method originally proposed by Schardin [11]. Despite the historical development, the name background-oriented schlieren technique is the most common, and the BOS acronym is the best known. Updated reviews of the current state of the art in this field are given in [12,13].

Recently, diffractive optical element (DOE) based BOS technique, strictly resembling Schardin's schlieren #2 technique, was proposed for flow visualization [14]. The technique relies on projecting a fringe pattern generated by the DOE element through a phase object or test section, and recording the deformed fringe patterns caused by heating the test section. Subsequently, fringe analysis methods [15] can be applied for fringe pattern demodulation or phase extraction. In a recent work [16], application of fringe analysis methods based on Fourier transform method and windowed Fourier transform (WFT) method was studied and quantitatively compared with particle image velocimetry (PIV) method [17] for flow visualization, and WFT method was shown to have superior performance with respect to other methods. Though DOE based schlieren technique offers the advantages of compactness, robustness and good measurement sensitivity, the ability to selectively investigate or visualize the heat flow features or structures on a spatial scale is lacking. Enabling such capability would impart great value addition to the schlieren technique and be of great significance for quantitative heat flow visualization.

The main aim of this paper is to enhance the capabilities of the DOE based schlieren technique for flow measurements using robust fringe processing and multi-scale visualization methods. The experimental setup for the DOE based schlieren technique and the applied fringe processing method is discussed in Section 2. Subsequently, theory of multi-scale analysis for the proposed technique is outlined in Section 3. The results are presented in Section 4. These are followed by discussions and conclusions.

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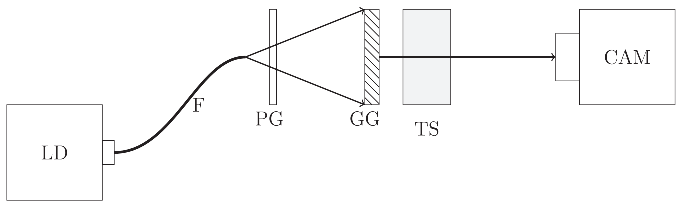

Fig. 1. Schematic. LD: Laser Diode, F: Single mode optical fiber, PG: Phase grating, GG: Ground glass, TS: Test Section, CAM: Camera .

2. Experimental setup & fringe processing

The schematic of the diffractive optical element based BOS setup is shown in Fig. 1. The illumination source is a laser diode (Lasiris, wavelength $\lambda = 638.5$ nm, output power 5 mW) which is pigtailed to a single mode fiber. The fiber end, which acts as a point source, emits spherical waves which impinge on the diffractive optical element (DOE). The DOE is a blazed phase grating realized on index-matching epoxy, and acts as a beam divider in our setup. The beams emerging from the grating form interference fringes or fringe pattern in the superposition region. The fringe period for the fringe pattern can be controlled by changing the distance between the fiber end and grating. The fringe pattern is projected on a ground glass plate which acts as a screen. The test section consisted of rib-roughened vertical channels (details described in [18]) and is placed in front of the ground glass plate. The aluminum rib has a square section with a height of 0.00485 m. The investigated phenomenon is the natural convection heat transfer with air as the convective fluid. A TV camera, focused on the screen, is used to view the background pattern through test section. The opacity of the glass is not critical; as the role of the ground glass is to act as a screen for the fringes, traditional ground glasses can be used. More details about the setup are outlined in [14], while the effects of changing the period of the fringe pattern and the distance between the test section and ground glass are discussed in [16].

In this setup, the beam passing through the test section is deflected due to the spatial variations or fluctuations in the refractive index induced by temperature gradient. The deflection angle is directly proportional to the temperature gradient [14]. As the fringes are seen through a medium (air) with a spatially varying index of refraction (because of the heat transfer phenomenon), the result is a displacement of the pattern, or, equivalently, a phase modulation. Subsequently, the phase modulated or deformed fringe pattern recorded on the camera can be modeled as

$$I(x, y) = a[1 + \cos[2\pi f_x x + \phi(x, y)]]$$

where a is the amplitude term, f_x is the carrier frequency dependent on the grating period and $\phi(x, y)$ is the phase term introduced due to temperature gradients.

As a first step, we captured the fringe pattern corresponding to the initial state where no heating was applied to the rib. This reference fringe pattern is shown in Fig. 2(a). Note that we applied a mask of zeros for the region occupied by the rib in all images, as there are no fringes in this region. Subsequently, the rib was heated, and the refractive index changes caused by temperature gradient variations lead to a phase modulated fringe pattern. Denoting the temperature variation with respect to the initial state as ΔT, we recorded the fringe patterns corresponding to $\Delta T = 5\,^\circ$C, 11 °C and 18 °C, which are shown in Fig. 2(b–d).

As the information about the temperature gradient is encoded in phase, the next step in our approach is fringe demodulation or reliable extraction of the embedded phase map from the deformed fringe pattern. For phase retrieval, we applied the windowed Fourier transform (WFT) method [19] which relies on local processing of the fringe pattern by using a two-dimensional block or window, which is usually selected to be a Gaussian function. Effectively, the Fourier transform of the windowed signal is computed and analyzed, as opposed to the whole signal operation of the conventional Fourier transform. The method enables local fringe processing and remedies the problems associated with the global nature of the Fourier transform. More details about the implementation and working of the WFT method for processing DOE BOS fringes are presented in [16]. For each ΔT, the relative phase between the reference and the corresponding phase modulated fringe pattern was computed using the WFT method.

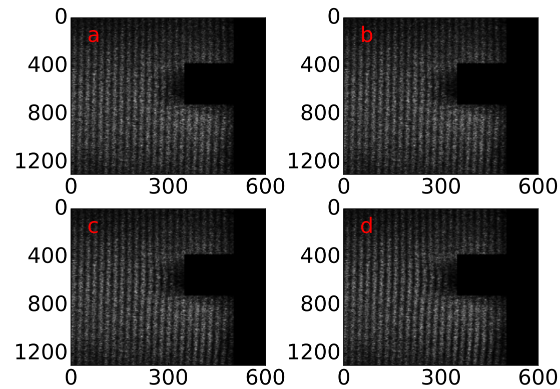

Fig. 2. (a) Reference fringe pattern. Fringe patterns obtained for $\Delta T = 5\,^\circ$C, 11 °C, and 18 °C in (b–d). The values on the axes represent the number of pixels along the horizontal and vertical directions.

3. Theory

The two-dimensional spatial phase distribution recovered in our setup is directly related to the temperature gradients, as mentioned before. The next task is to apply multi-scale analysis of the phase image to analyze the features at different scales or resolutions. This is performed using the two-dimensional continuous wavelet transform (2DCWT). For the phase function $\phi(x, y)$, the wavelet transform can be expressed as [20,21],

$$W(x_1, y_1, \alpha) = \frac{1}{\alpha} \iint \phi(x, y)\psi^*\left(\frac{x - x_1}{\alpha}, \frac{y - y_1}{\alpha}\right) dx dy \quad (1)$$

where $\psi(x, y)$ is the mother wavelet, and * denotes the complex conjugate. Also, (x_1, y_1) indicates the translation of the mother wavelet in the 2D space and dilation is represented by the scale parameter α. Effectively, the wavelet transform can be represented as the correlation of the signal ϕ with the translated and dilated version of the mother wavelet ψ. Regions where the wavelet transform values are large indicate high correlation between the signal and the wavelet. Note that the angular dependence of the 2DCWT is not considered here for the sake of computational simplicity.

Because of the correlation operation, the computation of the wavelet transform can be efficiently performed in the Fourier domain. The Fourier transform of the wavelet is given as

$$\hat{W}(f_x, f_y, \alpha) = \alpha\hat{\phi}(f_x, f_y)\hat{\psi}^*(\alpha f_x, \alpha f_y) \quad (2)$$

where f_x and f_y indicate the spatial frequencies, and $\hat{\phi}$ and $\hat{\psi}$ denote the 2D Fourier transforms of phase ϕ and mother wavelet ψ. Hence, the 2DCWT can be computed using an inverse Fourier transform,

$$W(x_1, y_1, \alpha) = \iint \alpha\hat{\phi}(f_x, f_y)\hat{\psi}^*(\alpha f_x, \alpha f_y) e^{i2\pi(f_x x_1 + f_y y_1)} df_x df_y \quad (3)$$

By using fast Fourier transform algorithm for evaluating the Fourier transform, high computational performance can be achieved.

For our analysis, we chose the isotropic 2D Mexican hat function as the mother wavelet [20,22],

$$\psi(x, y) = (2 - x^2 - y^2)\exp\left[-\left(\frac{x^2 + y^2}{2}\right)\right] \quad (4)$$