Natural Thermal Convection Field Measurement Technology Based on Background Oriented Schlieren Technology

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Abstract. Background oriented schlieren technology is developed from the combination of schlieren technology and PIV technology. It is an emerging non-contact flow field quantitative measurement method. The development and principle of background oriented schlieren technology are introduced in detail. A set of background oriented schlieren imaging system suitable for natural thermal convection field is built. The quantitative measurement research is carried out on the natural thermal convection field above the candle flame, and the density field is calculated. Distorted vector displacement map. The results show that the background oriented schlieren technology can be better applied to the quantitative measurement of natural thermal convection field, and it has broad development prospects.

1. Introduction

Background oriented schlieren technology (BOS) is a non-contact quantitative measurement method that determines the refractive index change of the flow field based on the deflection of light. Compared with schlieren technology, BOS technology has obvious advantages. First of all, BOS can only be applied to the qualitative display of flow field density, while background schlieren technology combines particle tracing image processing technology (PIV) and schlieren technology [1]. By calculating the offset of the background spots quantitatively obtain the amount of light deflection in a certain area. Secondly, the background schlieren technology does not require the sophisticated and expensive optical instruments in the traditional schlieren technology, and the measurement of a larger field of view can be achieved only through the camera and the background image. At the same time, with the cooperation of multiple cameras, multi-angle measurement of the flow field can be achieved. Through the application of computer tomography (Computed Tomography, CT) etc [2], to process the integrated value of the flow field density and refractive index, the three-dimensional reconstruction of the flow field can be realized. In addition, through the frame-by-frame recording of a high-speed camera, the flow field can be measured with time evolution characteristics. Therefore, this technology is of great significance for density measurement and reconstruction of the density distribution of random media such as flow fields.

BOS technology is developed by Meier et al. on the basis of traditional schlieren technology through long-term experiments and theoretical accumulation [3]. In 2000, Raffel et al. further improved the BOS technology and applied this technology to the visualization of the density field of the helicopter blade tip turbine in hovering flight, verifying the feasibility of the background schlieren technology [4]. In 2004, Venkatakrishnan and Meier [5] used BOS technology to obtain the density field...
of axisymmetric supersonic flow on a cone-cylinder model, and found that there is an excellent correlation between the density field obtained by BOS and the data from the cone table. In 2009, Atcheson and Heidrich evaluated the performance of the optical flow algorithm in BOS, and pointed out that the performance of BOS can be significantly improved by combining the optical flow algorithm and multi-scale background. In 2010, Mizukaki T [6] tried to use high-speed background schlieren technology (Hi-BOS), and at the same time used a high-speed camera as a recording device to verify the flow visualization. Ota. M [7] of Chiba University in Japan proposed the CGBOS system, introduced the color grid background image into the BOS system and obtained the density gradient image of the model in the supersonic wind tunnel, and studied the supersonic density field and jet density field.

At present, BOS technology is widely used in aerospace, wind tunnel flow field measurement, heat and mass transfer and other fields abroad. But domestic research in this field is less and the technology is not mature enough. Based on the BOS technology, a non-contact temperature field measurement device suitable for natural thermal convection field is designed in this paper. The natural thermal convection field above the candle flame is image-recorded, and the PIV-based point recognition algorithm is used. The density gradient of the natural heat on the flow field is obtained. And the factors that affect the sensitivity of the BOS device are studied.

2. BOS measurement principle

The BOS method is a kind of schlieren technique, but the BOS can quantitatively measure the density distribution of the flow field. The traditional schlieren method uses a filter or a knife edge at the focal point, and uses the refraction of light caused by the density gradient of the observation part as a color or shade change. In the BOS method, one side of the measured flow field is a camera, and the other side is a background image and light source. When the density of the measured flow field changes, the refractive index of the flow field will change. The light passing through the background image is deflected and projected onto the photosensitive element of the camera after passing through the flow field. The Lorentz-Lorentz equation expresses the relationship between the refractive index of the fluid and the density:

\[
\frac{n^2}{n^2 + 2} = \frac{4\pi}{3} N \alpha
\]  

Among them, \(n\) is the refractive index, \(N\) is the number of molecules per unit volume, and \(\alpha\) is the average polarizability. In the natural thermal convection field, the fluid medium is gas, so it can be simplified.

\[
\frac{n - 1}{\rho} = K_{G-D}
\]  

Among them, \(K_{G-D}\) is the gas’s Guess constant, \(\rho\) is the gas density, and \(n\) is the refractive index.

\[
\varepsilon = \frac{1}{n_0} \int_{z_1}^{z_2} \hat{n} \frac{\partial n}{\partial y} dz
\]  

Figure 1 shows the schematic diagram of the BOS technology. The left side is the background image and light source, the middle is the measured natural thermal convection field, and the right side is the camera. The horizontal line in the figure represents the light path when there is no flow field, and the dashed line represents the reverse extension line after the light is deflected by the flow field.
Figure 1 Schematic diagram of the BOS technology

It can be obtained by geometric relation

\[
\frac{\Delta y}{L_b + L_c} = \frac{\Delta h}{f}
\]  

(4)

In this formula, \(L_b\) is the distance from the background image to the natural flow field; \(L_c\) is the distance between the natural flow field and the imaging system; \(f\) is the focal length of the camera lens; \(\Delta h\) is the displacement of the light in the \(y\) direction of the camera's photosensitive element in the presence or absence of a flow field; \(\Delta y\) is the distance between the intersection of the reverse extension line of the light source and the light after the flow field is deflected and the background image. The relationship between deflection angle and \(L_b\) is

\[
\varepsilon = \frac{\Delta y}{L_b}
\]  

(5)

According to formula (4) (5)

\[
\frac{1}{n_0} \int_{z_{\Delta z}}^{z_{+\Delta z}} \frac{\partial n}{\partial y} dz = \frac{L_b + L_c}{L_b f} \Delta h
\]  

(6)

According to formula (2)

\[
n_0 = G \rho_0 + 1
\]  

(7)

\[
\frac{G}{\rho_0 G + 1} \int_{L_c - \Delta L_c}^{L_c + \Delta L_c} \frac{\partial \rho}{\partial r(x,y)} dL = \frac{L_b + L_c}{L_b f} \Delta h
\]  

(8)

Therefore, the integral value of the refractive index change can be expressed by \(L_b\), \(L_c\), \(f\) and \(\Delta h\).

3. Design of BOS system suitable for natural thermal convection field

The schematic diagram of the BOS experimental device used in this article is shown in Figure 2. The light path structure is simple and the flow field has strong applicability. Since the object of this experiment is the natural flow field above the candle flame, an ordinary high-speed digital camera and a background with continuous light sources can be used.
3.1. Background

Background schlieren systems mostly use jammed paper with a specific image as the background. Since the BOS system is mostly in a relatively dark working environment, and the camera uses a very high shutter speed during exposure, additional light sources are often required for illumination to ensure successful exposure. The LCD screen can solve this problem. Based on the principle of BOS, this paper constructs a BOS system. The background part of the system uses LCD display as the background, the highest resolution is 1920×1080, and the highest brightness is 250 cd/㎡. The background image is drawn in Photoshop, and the background image is arranged vertically in a white straight line with a width of 3 pixels. Related research shows that the experimental results are better when the display pixels account for 10% to 20% of the total number of pixels [8], so the line spacing in the background image is set to 10 pixels, and the image size is 1920×1080. Aiming at the natural thermal convection field above the candle flame, in order to obtain a larger field of view, the LCD display screen is placed vertically. According to the actual measurement, the shape of the flow field is cylindrical, with a height of about 220mm and a diameter of about 100mm. Therefore, a 24-inch LCD display screen is more suitable.

3.2. The natural flow field

In order to present an ideal effect, the optical axis of the digital camera, the center of the background screen, and the smoothness to be measured need to be in the same straight line. Ordinary candles have a diameter of 20mm and will burn down 5mm per minute under normal lighting conditions. This led to the need to readjust the position of the candle during the experiment. In this experiment, multiple candles were melted and put into a beaker with a capacity of 100ml. The candle wick was fixed with a thin iron wire to ensure that it would not fall during the burning process. Experiments show that the self-made candle burns stably within 30 minutes, the height of the candle flame changes within 2 mm, and the shape of the candle flame remains almost unchanged. Therefore, this candle improves the stabilities of the experimental results.

3.3. Experimental parameter setting

According to the principle formula of background schlieren, the sensitivity of the system is inversely proportional to the distance between the flow field and the camera, and is proportional to the distance between the flow field and the background pattern. In this experiment, APS-C digital camera is used, the maximum resolution is 6000 pixels × 4000 pixels, the equivalent focal length of lens is 75mm, and the maximum aperture is F1.8. When the distance between the flow field and the background pattern increases, the aero optical effect of the flow field will increase significantly. As result, the distortion effect captured by the camera will be more obvious, and the picture definition will be lower. At the same time, with the increase of distance, the camera is restricted by its own optical conditions, so it is difficult to distinguish the pixels in the background pattern. Therefore, it is necessary to find the best
parameter settings according to the hardware conditions of the background schlieren system. In this experiment, the distance parameters are set as follows: the distance between the candle and the camera is 500mm, and the distance between the candle and the LCD screen is 1500mm. In order to achieve the best photography level of the camera, the aperture is adjusted to f2.2, ISO is 2000, and the shutter speed is 1/4000s.

4. Experimental results and analysis
This paper measures the flow field of natural heat above the candle flame. First of all, fix the relative positions of the LCD display, candle base, and digital camera to ensure that the optical axis of the camera is perpendicular to the center of the background screen. Since the candle flame is unstable and the natural heat above the candle flame is relatively weak to the flow field, this experiment needs to be carried out under no wind conditions. In order to prevent the movement of the human body from affecting the flow field of natural heat, a computer is used to remotely control the camera to complete the shooting.

After the camera background schlieren system is installed, use the digital camera to focus and meter the pattern on the LCD screen. In view of the weak light in the experimental environment and the low contrast of the background pattern, the camera's contrast focusing system will be difficult to work, so it is recommended to use the full manual mode of the digital camera. Take multiple background images without natural thermal convection and make sure that the relative distances and camera parameter settings remain unchanged in the next steps. Then fix and light the candle, and take a measurement image after the flame is stable, as shown in Figure 3.

In order to improve the quality and speed of later image processing, it is necessary to binarize the image. When a digital camera is shooting in a dark light environment, it will produce noise due to the improvement of ISO. Filtering the image can prevent the algorithm from mistaking the noise as useful spots. The processed image is shown in Figure 4.

PIV algorithm is used to analyze the cross-correlation of the experimental images. Fig. 5 shows the x-axis displacement vector nephogram, the y-axis displacement vector nephogram and the displacement vector image. According to the image, we can clearly see the structure of the flow field caused by natural heat above the candle. It can be seen that the structure near the flame is approximately symmetric. According to the distribution of speckle vector displacement nephogram, the vector displacement in the y-axis direction is generally greater than that in the x-axis direction, indicating that the main direction of convection in the flow field is in the y-axis direction. The results
show that the BOS technology can be used to quantitatively analyze the natural heat flow field.

Figure 5 Displacement vector of background point

(a) x-axis                                           (b) y-axis                                   (c) displacement vector

5. Conclusion
In this paper, based on the BOS technology, a set of non-contact flow field measurement and display device suitable for natural heat flow field is designed, and the flow field above the candle flame is taken as an example for experimental verification. Through the study of this paper, it can be seen that the natural flow field above the candle flame is a nearly symmetrical structure near the flame, and the disturbance phenomenon in the vertical direction is more obvious than that in the horizontal direction. With the further research of BOS technology, the research cost of non-contact quantitative measurement in aerodynamics, thermodynamics and other fields will be greatly reduced. Therefore, BOS technology has great research value.

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