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Development of unsteady background-oriented schlieren system in an indraft supersonic wind tunnel

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Development of unsteady background-oriented schlieren system in an indraft supersonic wind tunnel

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Abstract. To visualize the flow in the test section of an indraft supersonic wind tunnel in the University of Glasgow as long as possible, a background-oriented schlieren system was built up preliminarily. A MATLAB program based on a random dot algorithm developed in this study provides a fully customizable tool to generate background patterns with different sizes and dot densities. Background patterns produced by the in-house developed program then can be printed by a common ink-jet printer. To enhance the signal-noise ratio of the measurement system, white reflective film sheets, or semi-transparent paper can be employed. The correlation algorithm base on fast Fourier transform that is also applicable for PIV was chosen to process background oriented schlieren images. A validation test was performed to visualize the flow structure around a Pitot tube at M = 2.0. The experimental result proves that the BOS system established in this study is capable of visualizing the supersonic flow structure around the Pitot tube and sensitive enough to reveal weak density changes produced by the boundary layer, expansion waves, and weak oblique shock waves. Next, the current BOS system will be improved further by increasing the intensity of light sources to shorten the exposure time, using new cameras with better spatial resolution, and optimizing the background pattern.

1. Introduction

The background-oriented schlieren (BOS) has been widely used in wind tunnel testing [1-6] and scientific studies [7-9] because of its simplicity and flexibility. Compared with the conventional schlieren technique, BOS is capable of visualizing a very large field without expensive, large, and precision optics [10-12]. Also, it provides unique solutions to some specific problems, such as the large fields-of-view in aircraft flight tests and outdoor explosions [13-15], and schlieren imaging for large industrial wind tunnels [2, 16], especially when the test sections do not have sufficient optical access for conventional schlieren.

An indraft supersonic wind tunnel [17] was designed to conduct investigations on shock wave related phenomena in 2016 at the University of Glasgow. The tunnel has a test section area of 101.60 mm × 54.42 mm and 742.95 mm long. The maximum measurement size of the conventional schlieren system in the University of Glasgow is 203.3mm, which is limited by the diameter of the parabolic mirrors. To visualize the flow in the whole test section in a single run, a BOS system was built up preliminarily in this study. A MATLAB program based on a random dot algorithm was developed to produce digital background patterns with different sizes and dot densities, which can be printed by a common ink-jet printer. To enhance the signal-noise ratio of the measurement system, white reflective film sheets, or semi-transparent paper can be employed. The correlation algorithm base on fast Fourier transform that is also applicable for PIV was chosen to process background oriented schlieren images. This paper also presents the preliminary result of a validation test in the indraft supersonic wind tunnel.

2. Unsteady BOS system

2.1. Background pattern generation

The sensitivity and resolution of the BOS technique are determined by the quality of the background pattern to some extent. Previously, BOS background patterns can be produced by splashing droplets of paint with a brush directly on white paper sheets or wind-tunnel walls [18], projecting laser speckles generated through ground glass [19], or generating randomized monochromatic or colored pixel segments [20, 21]. In this study, a MATLAB program based on a random dot algorithm is developed to generate digital background patterns. The program outputs random dots with a customizable number, diameter, and size. The filled surface ratio that is the core parameter for background patterns can be controlled by the dot number when the dot diameter and background pattern size are fixed. Figure 1 illustrates the interface of the MATLAB program. Background patterns produced by this program then can be printed by a common ink-jet printer. To enhance the signal-noise ratio of the measurement system, white reflective film sheets, or semi-transparent paper can be employed.

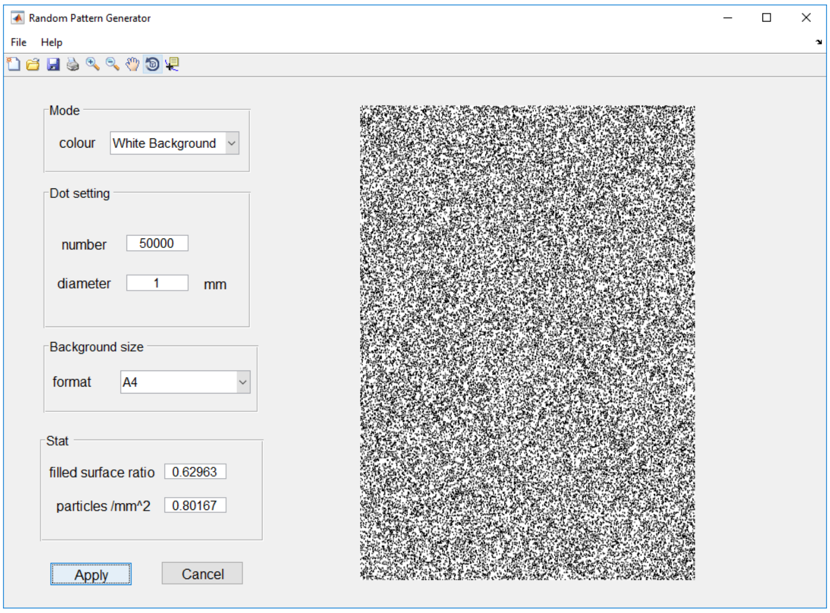

Figure 1. The MATLAB program for generating digital background patterns.

Generally, to assure the sensitivity and the resolution of the BOS measurement system, an individual random dot should yield 3–5 pixels in the final BOS images. Therefore, the optimal dot diameter of the background pattern is determined by the spatial resolution of the camera used in the BOS system and the specific experimental setup including the focal length of the lens f and the distance from the background pattern to the camera. A group of background patterns with different sizes and dot diameters need to be prepared for different occasions.

2.2. Image acquisition system

As discussed above, the BOS measurement system is much simpler than that of conventional schlieren photography without requirements for large and precision optics [10-12]. The BOS system developed in this paper consists of a background pattern, a Xenon arc lamp, and a fast camera with a group of lenses.

For an unsteady BOS system, a relatively high power light source is usually needed to obtain a large frame rate and small exposure time. Herein, the 450-1000W Xenon arc lamp from the Newport Corporation in the conventional high-speed schlieren system of the University of Glasgow [22] was tested in this study. Photron FASTCAM SA1.1 camera was selected as the time-resolved imaging device with a 1024×1024 pixel spatial resolution at frame rates up to 5,400 frames per second. With a smaller region of interest (ROI), this camera can record images at a maximum frame rate of 675,000 fps.

2.3. Image post-processing

The cross-correlation algorithm base on fast Fourier transform that is also applicable for PIV was chosen to process background oriented schlieren images, which mainly involves a statistical pattern matching searching the dot pattern from the interrogation area A in an image back into the interrogation area B in the other image of an image pair [23]:

$$C(m,n) = \sum_i \sum_j A(i,j)B(i-m, j-n) \tag{1}$$

where A and B are corresponding interrogation windows from image A and image B. The most probable displacement of the interrogation window from A to B is determined by the location of the intensity peak in the resulting correlation matrix C [23]. The aforementioned cross-correlation process is performed by an open-source PIV software, PIVlab in this study. Detailed information regarding how to use this software can be found in its user manual [24].

Wind tunnel facility and experimental setup

Figure 2 gives the CAD assembly of the indraft supersonic wind tunnel in the University of Glasgow, which is preliminarily designed for shock train control with a throttle plate downstream of the test section and also can run as a conventional supersonic wind tunnel. The tunnel has a test section area of 101.60 mm × 54.42 mm and 742.95 mm long. Two nozzles for Mach 2.0 and 4.0 were designed and fabricated. The maximum measurement size of the conventional schlieren system for this tunnel was only 203.3mm and is not capable of covering the whole test section, which is the primary motivation to develop a BOS system. The running time of this tunnel is up to 10s with a 34 m^3 vacuum tank. There are optical accesses on the two side test section walls and the ceiling wall to conduct optical measurements including schlieren, DIC, PIV, and PSP.

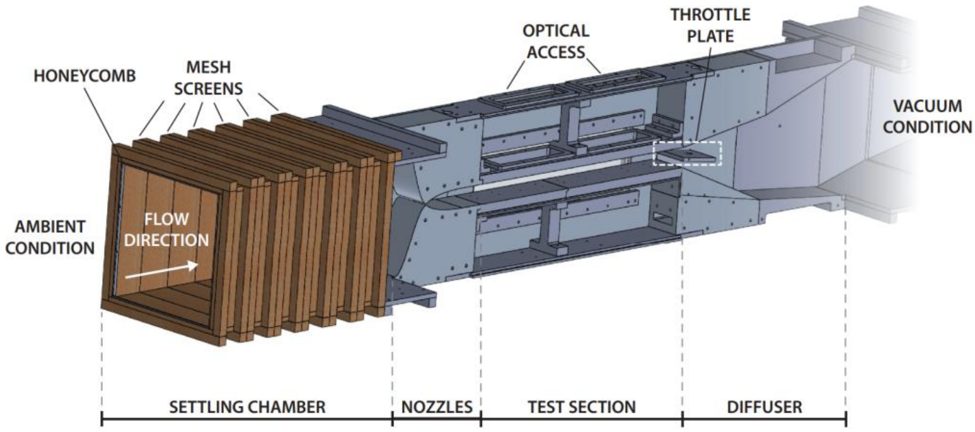

Figure 2. The design of the indraft supersonic wind tunnel [17].

To validate the BOS system, a Pitot tube test in the supersonic wind tunnel was visualized. Figure 3 shows the schematic of the BOS experimental setup in the indraft wind tunnel. Specifically, a random-dot pattern with a dot diameter of 1 mm and the filled surface ratio of 63% was printed using a semi-transparent paper sheet to increase the signal-noise ratio and shorten the exposure time. A reference image without the flow was recorded ahead of each run. Afterward, a set of test images were acquired to visualize the flow structure evolution around the Pitot tube. In this study, the framing rate is 1000 fps with an exposure time of 33μs. The distances from the background pattern to the center of the test section, Z_D, and to the lens of the camera, Z_B, were 1000 mm and 1800mm respectively.

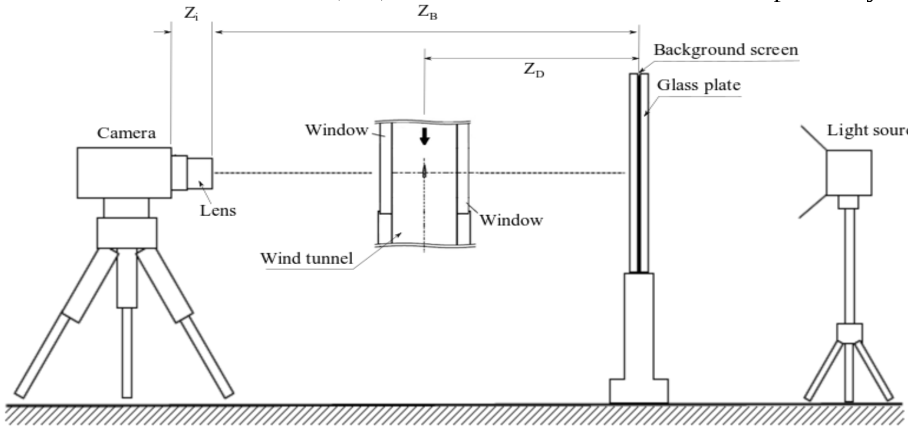

Figure 3. Experimental setup of the BOS test

3. Results and discussion

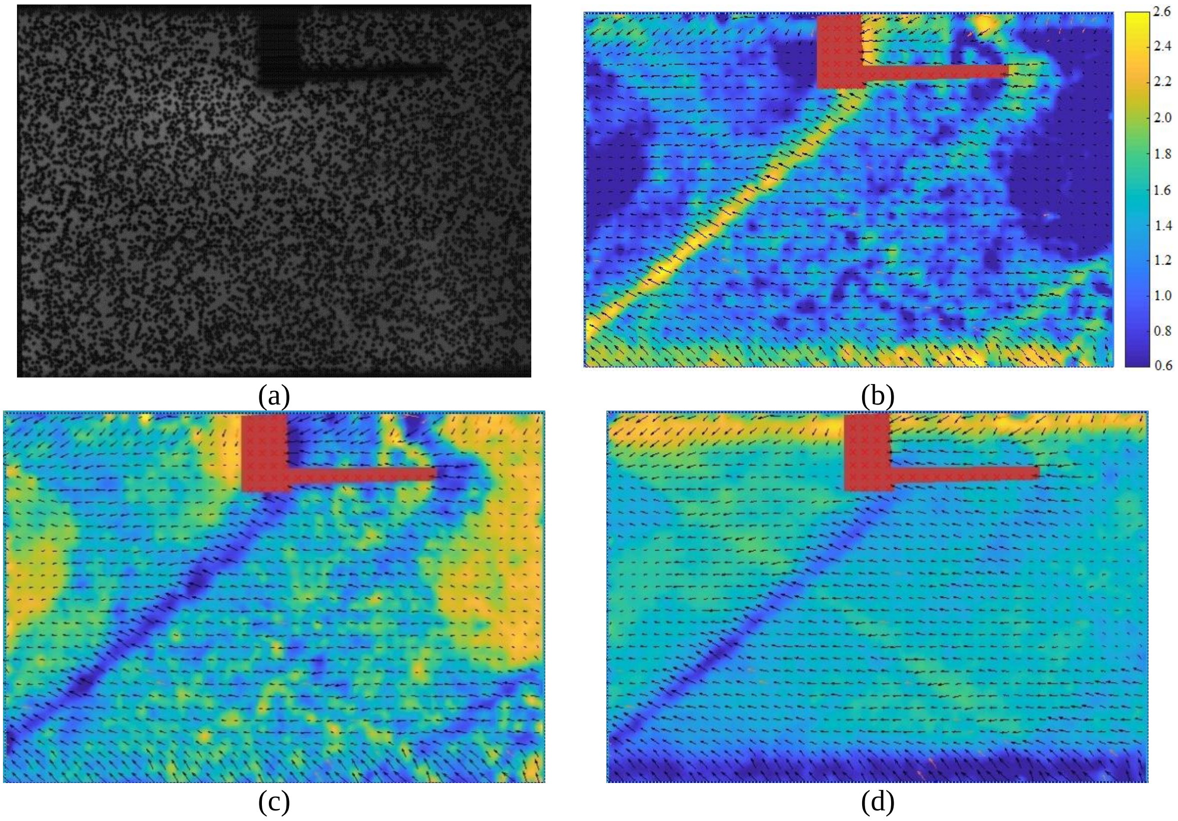

Figure 4 BOS results of the validation test at *M*=2.0: (a) raw test image; (b) BOS displacement result in pixels; (c) horizontal displacement distribution; (d) vertical displacement distribution

Figure 4 shows the preliminary BOS results of the validation test. As can be seen from Fig. 4 (a), a Pitot tube was mounted on the upper wall of the test section. Because the fast camera generally focuses on the background pattern for the best image contrast, a small aperture diameter was chosen to increase the depth of field of the imaging system and obtain good sharpness for the Pitot tube and the flow in the test section. Therefore, raw BOS images were relatively dark due to the limit of the power of the light source. To improve the quality of BOS images, contrast limited adaptive histogram equalization (CLAHE) was performed before the cross-correlation. Figures 4 (c) and (d) provide the horizontal and vertical displacement distributions from one BOS image respectively. From the horizontal displacement field, the flow structure representing density variation in the *x*-direction including expansion waves, the oblique shock wave, the bow shock ahead of the Pitot tube, and the normal shock ahead of the Pitot tube root can be revealed well. By contrast, flow features representing density change in *y*-direction such as the boundary layer and the oblique shock wave are visualized in the BOS vertical displacement distribution result. The capability of dissolving the density change into two directions is one of the primary advantages of the BOS system, which is difficult to accomplish for the conventional schlieren technique. Figure 5 illustrates the main flow structure around the Pitot tube. It is apparent that the BOS system established in this study is capable of visualizing the supersonic flow structure around the Pitot tube and sensitive enough to reveal weak density changes produced by the boundary layer, expansion waves, and weak oblique shock waves.

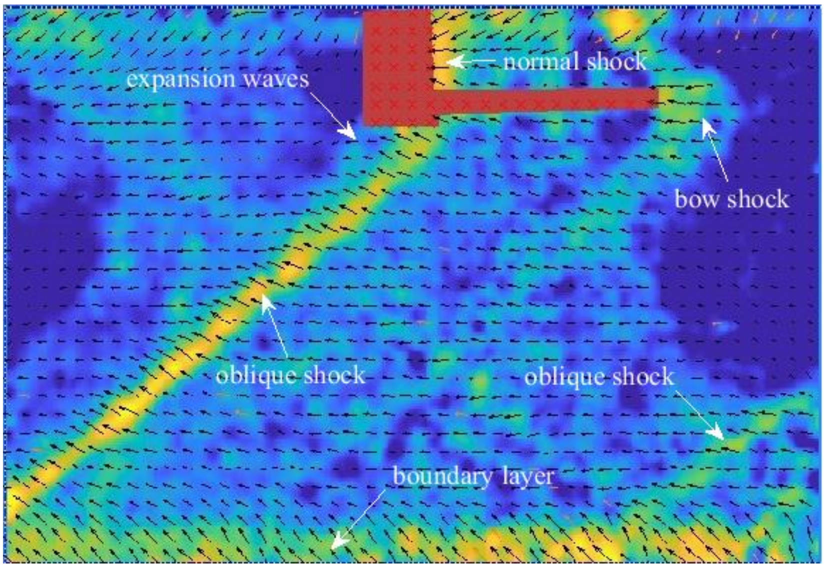

Figure 5. Flow structure around the Pitot tube.

However, it also can be seen from Figure 4 and Figure 5 that shock waves visualized by the current BOS system are quite thick and blur. The location evolution of the shock wave from different BOS sequences demonstrates that the bow shock ahead of the Pitot tube nose, the oblique shock wave, and the normal shock wave around the Pitot tube root present an oscillation feature to some extent. Because of the shock oscillation and the long exposure time (33μs) that is limited by the intensity of the light source, shock waves visualized from the current BOS system are relatively blurred. Next, extra light sources will be added to shorten the exposure time.

4. Conclusions

An unsteady background-oriented schlieren (BOS) system was preliminarily established in an indraft supersonic wind tunnel at the University of Glasgow. To validate the sensitivity and capability of the BOS system, a Pitot tube test in the supersonic wind tunnel was performed. A random-dot pattern with a dot diameter of 1 mm and the filled surface ratio of 63% was printed using a semi-transparent paper sheet to increase the signal-noise ratio and shorten the exposure time. Based on the BOS horizontal displacement field, flow structures representing density variation in the x-direction including expansion waves, the oblique shock wave, the bow shock ahead of the Pitot tube, and the normal shock ahead of the Pitot tube root can be revealed. By contrast, flow features representing density change in y-direction such as the boundary layer and the oblique shock wave are visualized in the BOS vertical displacement distribution result successfully. However, shock waves visualized from the current BOS system are relatively thick and blur because of the shock oscillation and the long exposure time (33μs) that is limited by the intensity of the light source. Next, the current BOS system will be improved further by increasing the intensity of light sources to shorten the exposure time, using new cameras with better spatial resolution, and optimizing the background pattern.

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