Reconstruction of Unsteady and Axisymmetric Flow Field by Colored-Grid Background Oriented Schlieren (CGBOS) Technique

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1 Introduction

The Background Oriented Schlieren (BOS) technique was proposed by Meier [1], and it enables us to take a quantitative density measurement of a flow field with computer-aided image analysis. In the past several years, the BOS technique was applied in various experiments [2],[3]. The principle of BOS is similar to that of the conventional schlieren technique, it exploits the bending of light caused by a change of the refractive index corresponding to the density change in the medium. Both techniques are sensitive to the density gradient. The conventional schlieren technique employs many optical elements, such as a pinhole, concave mirror, knife edge, color filter, camera, etc. However,because the conventional technique cannot easily provide a quantitative measurement, it is commonly used for qualitative measurement, such as flow visualization. In contrast, BOS requires only a background and a digital camera to realize the quantitative measurement of density. Figure 1 shows an optical setup for the BOS technique [2]. If the density is changed between a background and a camera, background image is captured at the image sensor of digital camera with displacement Δh because of the refraction of the light passing through the density gradients, shown as a solid line in the figure. The relation between Δh and refractive index n is expressed as equation 1, where l_b denotes the distance from the background to the phase object, l_c the distance from the phase object to the camera, l_i the distance from the camera lens to the sensor, f the focal length of the camera, n the refractive index, ε the deflection angle, and x and y the position in the projected

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plane [1]. The relation between density ρ and refractive index n is given by the Gladstone-Dale equation expressed as equation 2, where G is the Gladstone-Dale constant. The integration of spatial gradients of refractive index along the light pass can be obtained from equation 1 by calculation of the displacement Δh with image analysis. The density information can be also determined with equation 2.

In this paper the Colored Grid Background Oriented Schlieren (CGBOS) technique is applied to the measurement of unsteady shock waves around an axisymmetric body with a high-speed camera. The quantitative measurement results of unsteady and moving shock wave ahead of a circular body obtained with CGBOS technique are reported. Furthermore, the reconstruction of the density on the assumption that flow is axisymmetric is examined and the 3-D experimental data with time variation of unsteady and moving shock wave achieved by Computed Tomography (CT) and CGBOS technique are discussed.

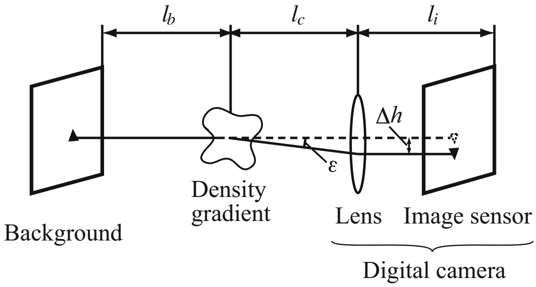

Fig. 1 Optical setup for BOS measurement.

$$\frac{1}{n_0}\int_{l_b-\Delta l_b}^{l_b+\Delta l_b}\frac{\partial n}{\partial R(x,y)}dl = \frac{l_b+l_c}{l_b f}\Delta h \tag{1}$$

$$\rho = \frac{n-1}{G} \tag{2}$$

2 Experiments

Experiments were carried out in a supersonic blow-down wind tunnel of ISL. The size of test section is 0.2 m × 0.2 m and free-stream Mach number was set to 3.0. The CGBOS images are recorded with a phantom v1610 high-speed camera with 27,000 fps (frames-per-second) and the exposure time was 36 μs. In order to increase the depth of field and the accuracy of CGBOS measurement, the telecentric optical system [4] are introduced. Figure 3 shows a setup with telecentric optical system. Focal length of the concave mirror is 1,500 mm and the camera lens is 300 mm. An aperture is installed at the focal position of both concave mirror and camera lens to capture the parallel light ray. Generally, normal BOS measurement captures the phenomena with the diverging light and sometimes it could cause the problems related with the view angle of camera lens. The parallel projection of the background and flow field can be obtained by telecentric optical system. In this report, the colored background is composed of blue and red stripes. The blue stripe is used for the horizontal background and the red for vertical, as shown in Figure 4. The distortion of the background image along the bow shock can be seen. The CGBOS image can be separated into blue (horizontal) and red (vertical) stripe images by the color information. The advantage of using colored background is that density gradients in vertical and horizontal direction can be obtained from one CGBOS image and it helps us to perform the experiments efficiently. The vertical distortion of the background image is obtained from the horizontal blue-stripes and the horizontal distortion is obtained from the vertical red-stripes. The displacements of each stripe pattern can be obtained by the comparison between the reference image generated by recording the background under the no-flow condition before experiment and the test image recorded under flow condition. The image analysis procedure is derived from the finite-fringe analysis technique of the LICT (Laser Interferometric Computed Tomography) measurement [5]. The accuracy of the proposed method for the steady flow can be found in Ref. [6].

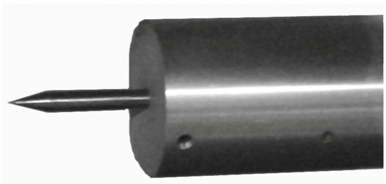

Fig. 2 Spike-tipped model.

3 Experimental Results

The 8-bit gray-scale images of vertical displacement of background are shown in Figure 5. The resolution of the captured image is 640 $\times$ 800 pixels with 27,000 fps. The black and white color represents the shift of the stripe in the lower and upper directions, respectively. Four images are continuos frame (from a to d) with 37 μs interval. The oblique shock wave from the tip of a spike, the bow shock in front of a circular body and their interaction are captured. These images clearly show a large scale instability of flow field.

The test model has axisymmetric geometry and the captured unsteady flow phenomena are almost axially symmetrical as shown in the displacement images of Figure 5. Therefore, three-dimensional density distribution of unsteady flow field is reconstructed with Algebraic Reconstruction Technique (ART) [7] on the assumption that the flow is axisymmetric in this paper. Earlier studies [6] showed that the reconstruction around an axisymmetric model can be obtained from 36 projection angles from 0^o to 175^o with intervals of 5^o. Figure 6 shows the reconstructed density distribution at the instant of c in Figure 5. Density distribution in two planes across

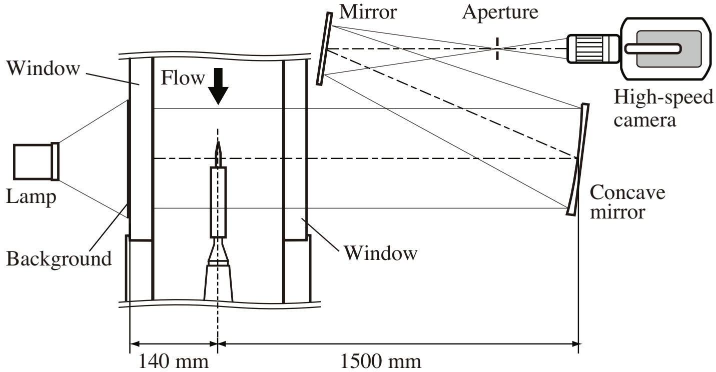

Fig. 3 Setup with telecentric optical system.

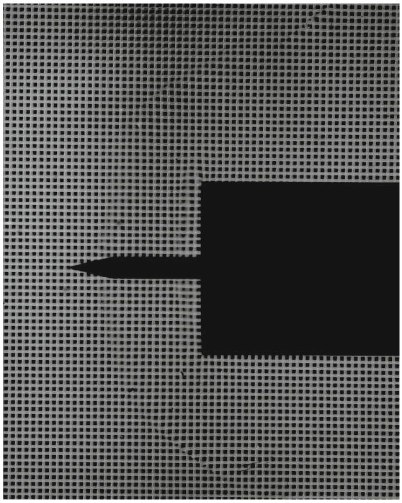

Fig. 4 CGBOS image under Mach 3.0 flow.

a central axis of a spike-tipped model are illustrated. The oblique shock from the tip of a spike and the bow shock in front of a circular body are exhibited. Time resolved 3-D density distribution of unsteady flow field (axisymmetric) can be obtained from the experiments by applying ART to every instants of time.

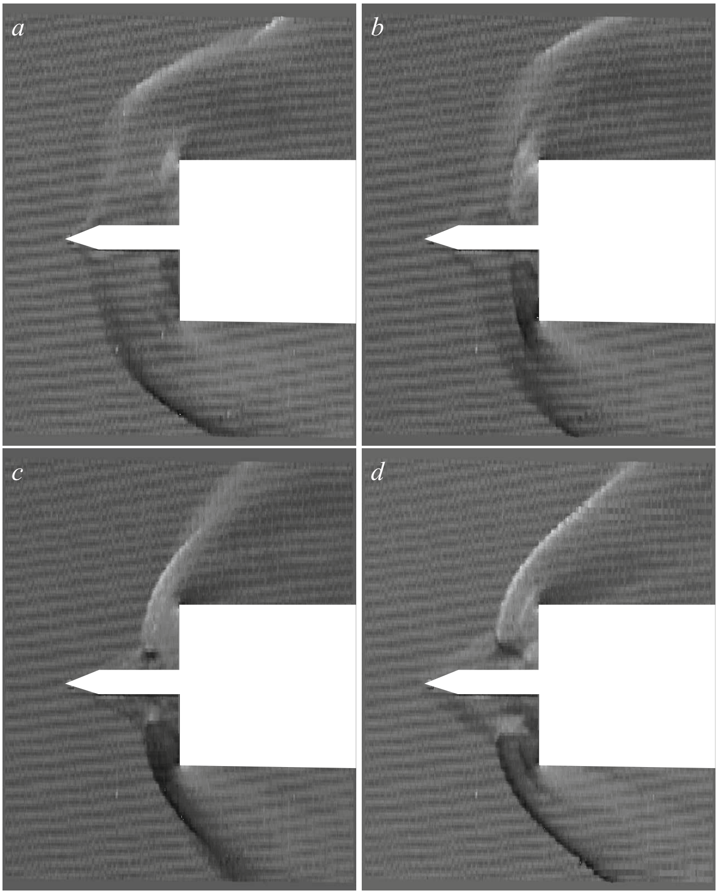

Fig. 5 Vertical displacement at different time ($\Delta t = 37\mu s$).

4 Conclusion

The CGBOS technique is applied to the measurement of unsteady flow field with a high-speed camera. As a result, a large-scale instability of flow is captured quantitatively. Furthermore, the ART is applied to reconstruct the density field on the assumption that the flow is axisymmetric. Time resolved 3-D density information of the axisymmetrical flow field can be obtained with the proposed procedure.

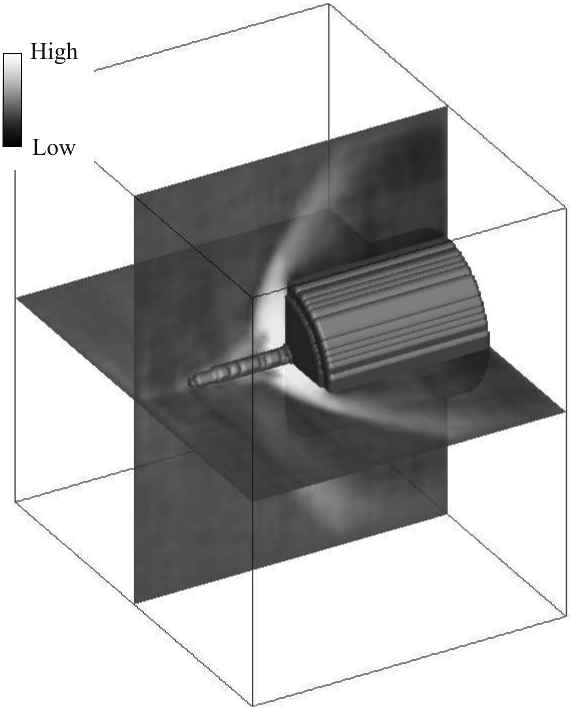

Fig. 6 Reconstructed density distribution.

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