QUANTITATIVE 3D DENSITY MEASURMENT OF SUPERSONIC FLOW BY COLORED GRID BACKGROUND ORIENTED SCHLIEREN (CGBOS) TECHNIQUE

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Abstract

The background oriented schlieren (BOS) technique is one of the visualization techniques that enable the quantitative measurement of density information in the flow field with very simple experimental setup. The principle of BOS is similar to conventional Schlieren technique, it exploit the bending of light caused by refractive index change corresponding to density change in the medium and both techniques are sensible to density gradient. In this report we propose the Colored Grid Background Oriented Schlieren (CGBOS) technique. The experiments were carried out in the 0.6 m × 0.6 m test section of supersonic wind tunnel at JAXA-ISAS. A colored grid pattern was used as background image and density gradient in vertical and horizontal direction was obtained. Computed tomographic reconstruction of 3D density information of supersonic flow field around asymmetric body from multi-directional CGBOS images is examined.

1 Introduction

The Background Oriented Schlieren (BOS) technique was proposed by Meier [1], and it enables us to have the quantitative density measurement with computer-aided image analysis. In the past several years, BOS technique had applied to various experiments - wind tunnel experiment [1]~[3], free flight experiment [3], free jet [3], [4], rotor blade tip vortex of full-scale helicopter [5], etc. The sensitivity and accuracy of BOS is examined by Goldhahn and Seume [4]. Recently Venkatakrishnan and Suriyanarayanan reported precise measurement of 3D density field of separated flow by BOS [6]. The principle of BOS is similar to conventional Schlieren technique, it exploit the bending of light caused by refractive index change corresponding to density change in the medium and both techniques are sensible to density gradient. Conventional Schlieren technique employs many optical elements - pinhole, concave mirror, knife edge or color filter, camera...etc, however it is difficult to realize quantitative measurement and this technique is commonly used for qualitative measurement like flow visualization. On the other hand BOS requires only a background and a digital still camera and it can realize the quantitative measurement of density.

2 Background Oriented Schlieren Measurement

Figure 1 shows optical setup for BOS technique [3]. If there is density change between the background and camera, background image is captured at CMOS sensor of digital still camera with displacement Δh because of the refraction of the light passing through density gradient as shown as a solid line. The relation between Δh and refractive index n is expressed as equation 1 where l_b denotes the distance from background to phase object, l_c the distance from phase object to camera, f the focal length of camera, n the refractive index and ε deflection angle [2]. 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 gradient of refractive index along light pass can be obtained from equation 1 by calculation of displacement Δh with image analysis. The density information can be also determined with equation 2.

Most of BOS techniques that have been applied to laboratory measurement employ monochromatic or colored random dot pattern as a background image. In these measurement two images are required - reference and test image. The reference image is generated by recording the background under no-flow condition before or after the experiment. The test image is recorded under flow condition and it contains disturbance with flow that causes the displacement of background. The displacement of dot pattern is calculated by comparing both images with cross-correlation algorithm commonly used in PIV (Particle Image Velocimetry) technique.

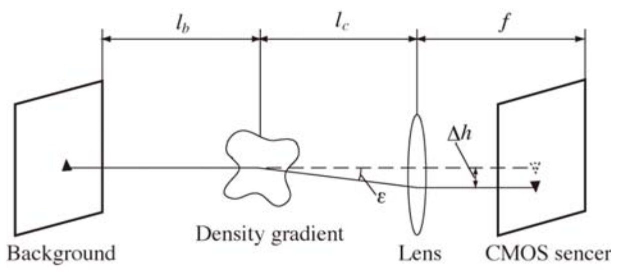

Fig. 1. Optical Setup for BOS

$$\Delta h = \frac{l_b f}{l_b + l_c} \frac{1}{n_0} \int_{l_b - \Delta l_b}^{l_b + \Delta l_b} \frac{\partial n}{\partial r} dl \qquad (1)$$

$$n = \rho G + 1 \qquad (2)$$

3 Experiments

The experiments were carried out in supersonic wind tunnel at JAXA/ISAS which has 60cm x 60cm test section. Figure 2 indicates a schematic diagram of an asymmetric body installed in the supersonic wind tunnel. The measurement system consists of metal halide lamp (continuous), background, and digital still camera (EOS Kiss Digital X) which has 3880 × 2690 pixels CMOS censor. The distance l_b and l_c are set to 710mm and 3820mm as shown in Fig. 3. The focal length of camera f is 320mm and shutter speed is set to 1/80 second. Thus the mean density field of supersonic flow is captured. Mach number of supersonic flow is set to 2.0. To obtain the multi-directional projection data for reconstruction, CGBOS images were obtained from nineteen projection angles from 0 degree to 90 degree with 5 degree

Fig. 2. Asymmetric Test Body

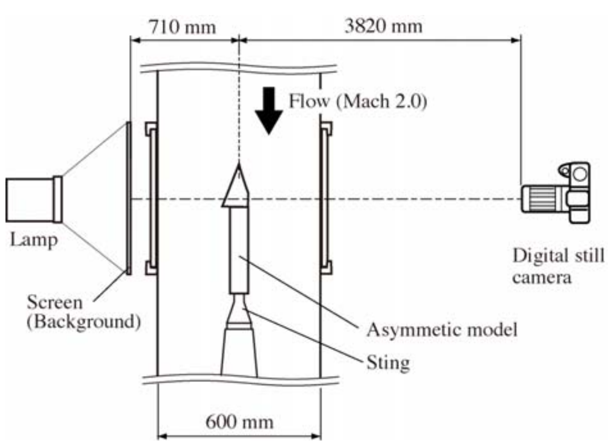

Fig. 3. Layout of CGBOS Measurement

intervals considering the symmetric nature of flow field. In this paper *x* axis is line-of-sight direction, *z* is along the free-stream direction, and *y* is the vertical axis and perpendicular to *x* and *z*.

4 Image Processing

Our research group has developed Laser Interferometric Computed Tomography (LICT) technique and succeeded to elucidate three-dimensional (3-D) unsteady and high-speed flow field behind discharging shock waves [7]~[10]. LICT technique employs Mach-Zehnder interferometer and N_2 pulsed laser as a light source to obtain the finite-fringe interferomgram, which represents projection image of flow field. The finite-fringe analysis method suitable for LICT measurement has also developed in our previous study. In this method the center of each fringe is calculated firstly. Secondary, the displacement of fringe pattern at designated position is calculated to obtain the projection data of density information at the position by comparing with fringe pattern at no-flow area. The projection data of whole flow field are obtained by calculating this projection data at all designated sections. Finally, quantitative 3-D density distribution of whole flow field can be reconstructed from multi directional projection data set obtained by this process.

We propose Colored Grid Background Oriented Schlieren (CGBOS) technique using colored-grid background. The two-dimensional (2-D) projection image of this colored-grid background exposed under flow condition supplies two directional (vertical and horizontal) density information and it can be obtained from only one test image. CGBOS technique does not require the reference image under no flow condition. Figure 4 shows CGBOS image taken through Mach 2.0 flow. In this report, colored

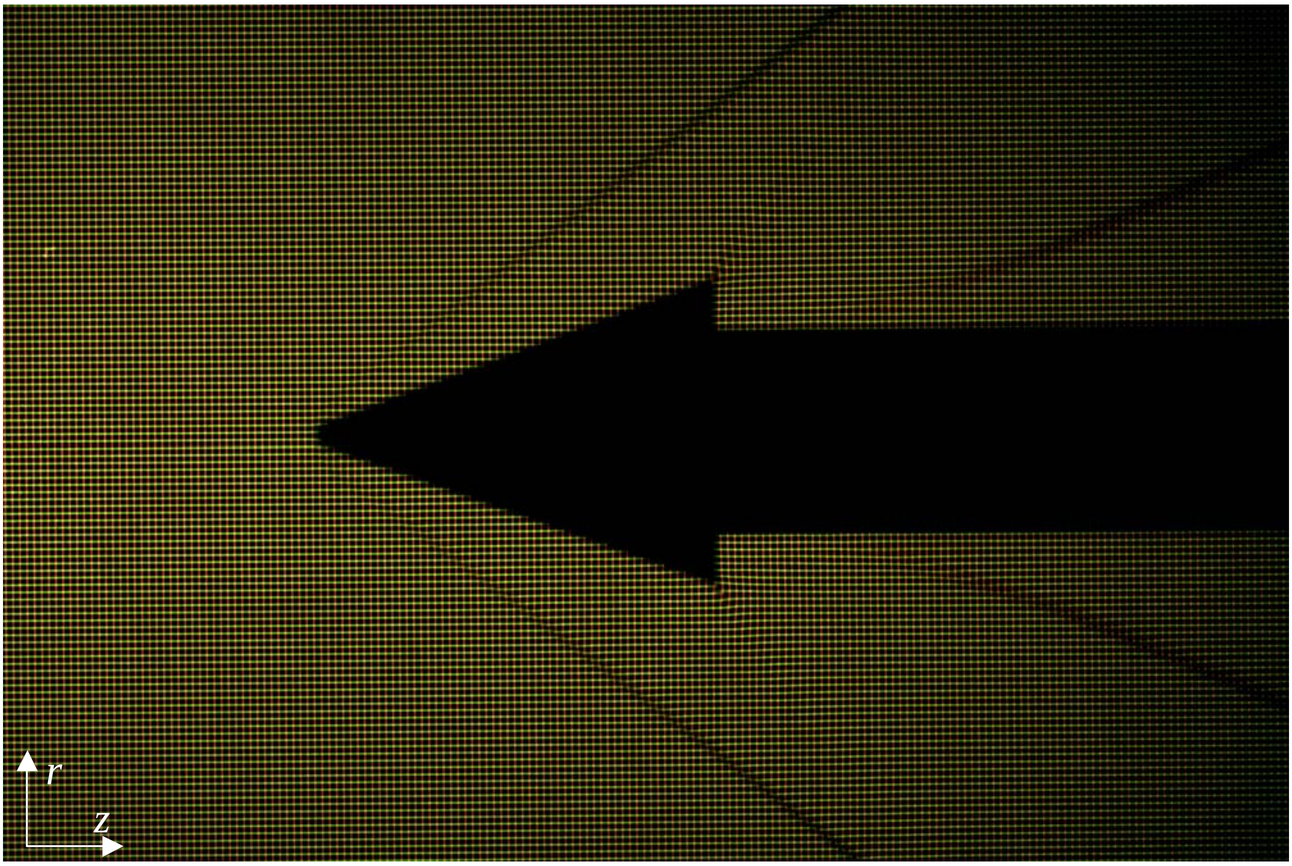

Fig. 4. CGBOS Image

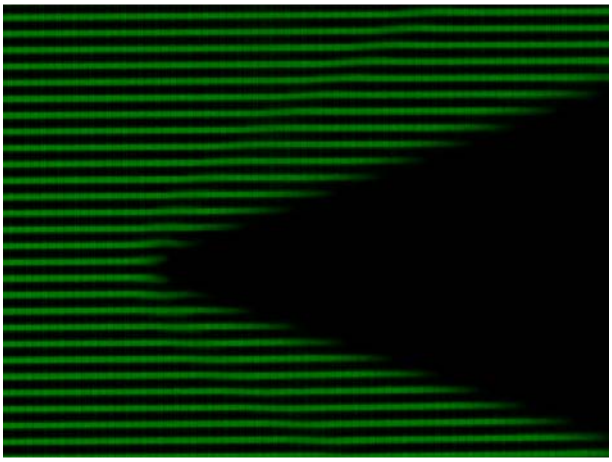

Fig. 5. Green Channel of CGBOS Image

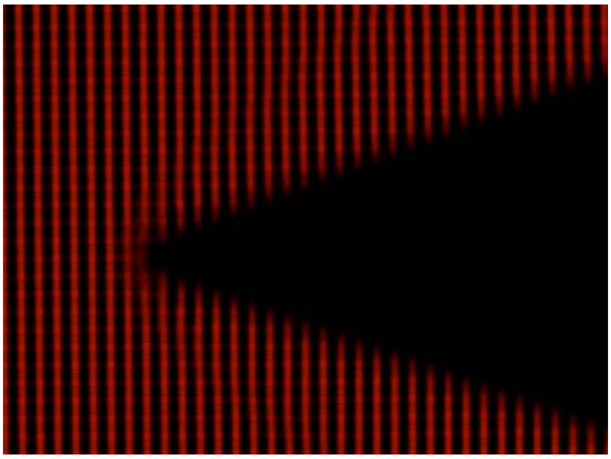

Fig. 6. Green Channel of CGBOS Image

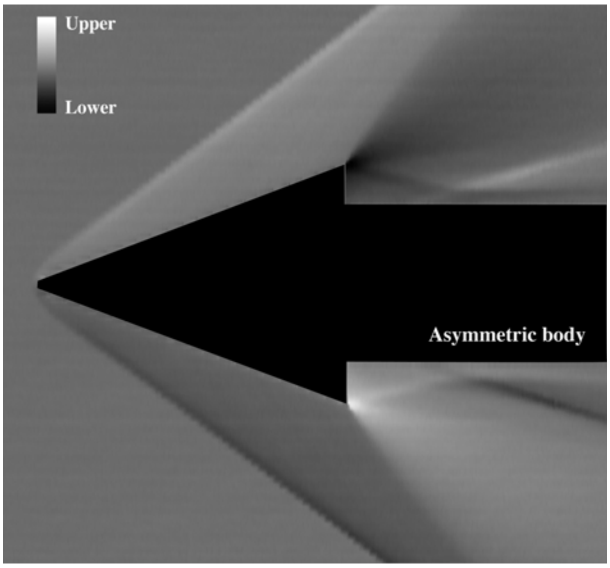

Fig. 7. Calculated Displacement of Horizontal Stripe

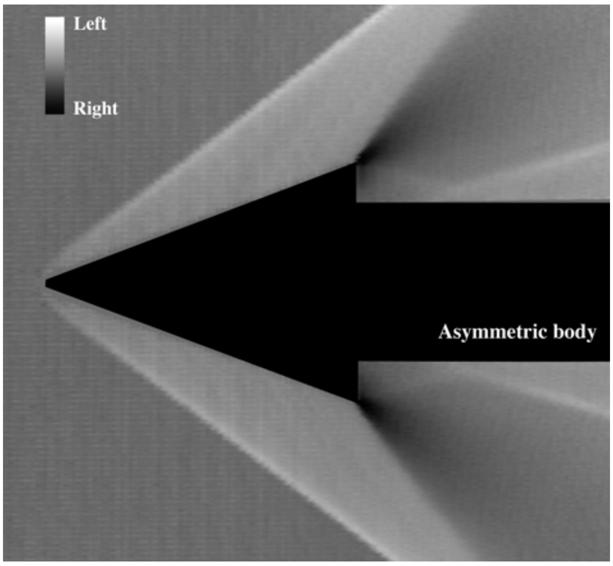

Fig. 8. Calculated Displacement of Vertical Stripe

background is composed of green and red stripes. The green stripe is used for horizontal stripe and red stripe for vertical. The distortion of background image along the shock wave and expansion fan is captured. CGBOS image can be separated into green (horizontal) and red (vertical) stripe image by color information. The distortion of background image in vertical direction is obtained from horizontal green-stripe and horizontal distortion is obtained from vertical red-stripe. Figure 5 indicates horizontal green-stripe image separated from CGBOS image of Fig. 4 and Fig. 6 indicates separated vertical red-stripe image from Fig. 4. The displacement of each stripe pattern in vertical and horizontal direction can be obtained with same finite-fringe analysis technique of LICT measurement mentioned above.

The gray-scale image of calculated displacement of Fig. 5 and Fig. 6 are shown in Fig. 7 and Fig. 8 respectively. Figure 7 indicates distribution of vertical displacement of horizontal stripe. Black and white color represents shift in lower and upper direction respectively. This image represents density gradient in vertical direction and equivalent to conventional schlieren image taken with horizontal knife-edge. Figure 8 represents horizontal displacement of vertical stripe. Black and white color represents shit in right and left direction respectively. This image represents density gradient in horizontal direction and equivalent to conventional schlieren image taken with vertical knife-edge. Bow shock generated from the tip of asymmetric model and expansion fan from inflection points of model are captured clearly. Both Fig. 7 and 8 are obtained from only one projected CGBOS image without averaging multi-exposed BOS images and they represent enough signal to noise ratio for reconstruction.

In CGBOS technique distributions of displacement of background image (Δh) are obtained quantitatively, Figure 7 and Fig. 8 represent projection data of density gradient as expressed in right hand side of Eq. 1. Therefore multi-directional CGBOS image were taken from 19 projection angles between 0 degree and 90 degree with 5 degree intervals considering symmetric nature of flow field. The projection data were obtained from 19 CGBOS images that supply separated 19 horizontal green-stripe images and 19 vertical red-stripe images. Three-dimensional density distribution of supersonic flow field around an asymmetric model is reconstructed from these 38 green and red projected images. In this paper, ART (Algebraic Reconstruction Technique) was employed for reconstruction.

The relation of projection angle θ and image plane is illustrated in Fig. 9. The vertical direction on projected plane is denoted by r as shown in this figure and Fig. 4. The gradient of refractive index in r direction is obtained from horizontal stripe image (Fig. 5) separated from CGBOS image. The gradient of n in x and y direction ($\partial n/\partial x$ and $\partial n/\partial y$) can be obtained with trigonometric relation between x, y, and r as shown in Fig. 9. The gradient of n in z direction ($\partial n/\partial z$) is obtained from vertical stripe image (Fig. 6). Three-dimensional density distribution is determined by following steps: Firstly, three-dimensional distribution of refractive index gradient in each direction ($\partial n/\partial x, \partial n/\partial y$, and $\partial n/\partial z$) is obtained by ART reconstruction. Secondly, three-dimensional distribution of $n(x, y, z)$ is determined by solving Poisson equation expressed in Eq. 3 using the Successive Over Relaxation method. Finally, normalized density distribution (ρ/ρ_0) is calculated by the relation between n and ρ. In Eq. 3 S is obtained by calculating the gradient of reconstructed $n(x, y, z)$ distribution.

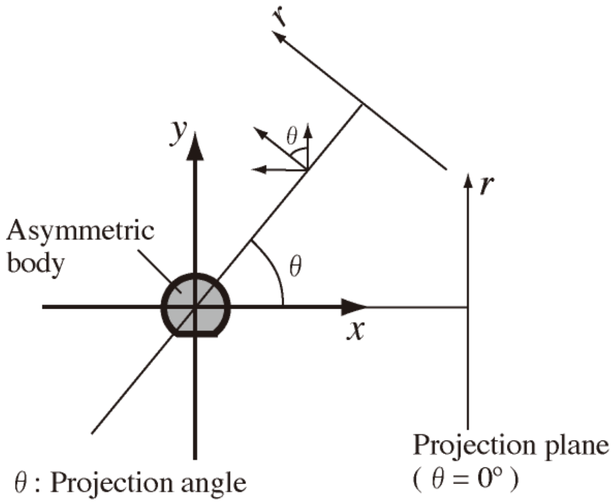

Fig. 9. Projection Angle and Image Plane

$$\frac{\partial^2 n}{\partial x^2} + \frac{\partial^2 n}{\partial y^2} + \frac{\partial^2 n}{\partial z^2} = S \qquad (3)$$

5 Results

Figure 10 shows contour of reconstructed density distribution on y-z plane (vertical plane in test section) crossing the central axis of an asymmetric body. Bow shock, expansion fan, and circulation zone behind spike in upper side of body are captured quantitatively. Figure 11 shows contour of density distribution on x-z plane (horizontal plane in test section) crossing the central axis of an asymmetric body. Circulation zones behind spike in both upper and lower sides of body are captured. The flow passing through spike separates and reattaches on body surface in downstream region, reattachment shock is generated as seen in Fig. 10 and 11. The circulation zone is disappeared in lower side of asymmetric body because there is a flat part instead of the corner of spike.

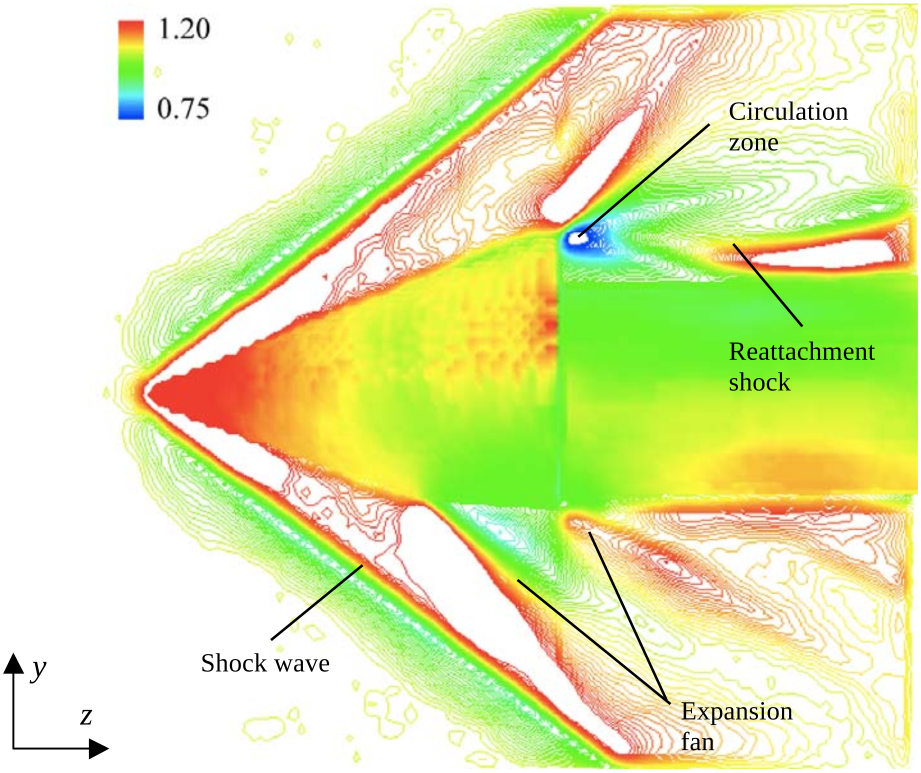

Fig. 10. Reconstructed Density Distribution on *y*-*z* Plane

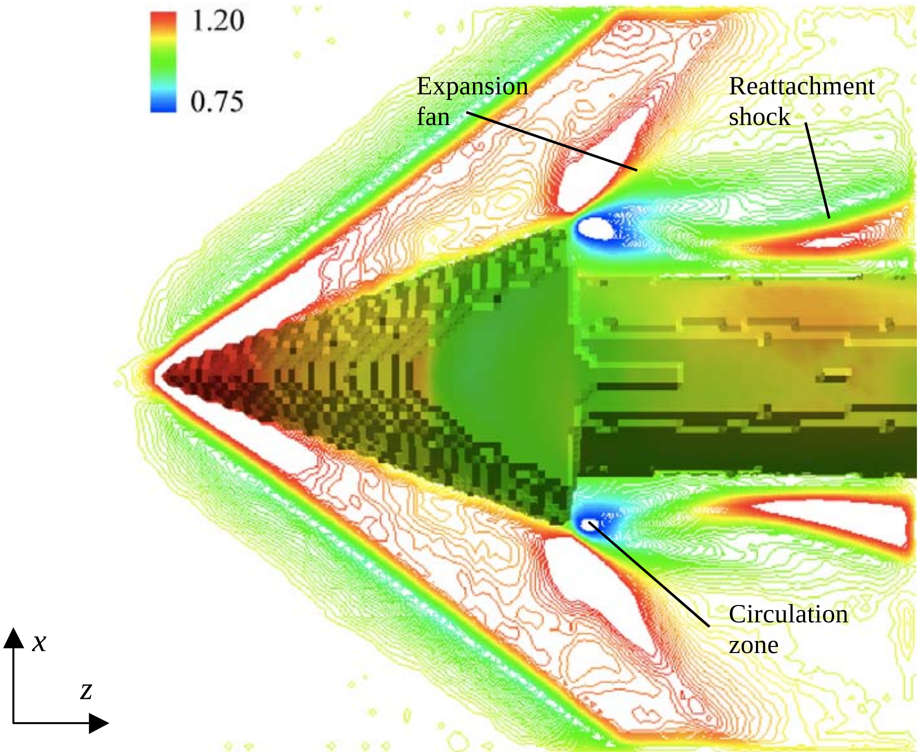

Fig. 11. Reconstructed Density Distribution on *x*-*z* Plane

6 Conclusions

The CGBOS technique using colored-grid background was proposed. The displacements of background in *r* and *z* direction on projected image were able to obtained from only one test image. The colored grid background was separated into horizontal and vertical stripes based on color information. The finite-fringe analysis technique was applied for calculation of displacement of separated stripe-patterns. The resultant images of displacement in vertical and horizontal direction supply good signal to noise ratio without averaging multi-exposures. Three-dimensional distribution of refractive index was reconstructed by ART and density distribution in an asymmetrical flow field was obtained quantitatively. Asymmetrical flow phenomena around an asymmetric model in Mach 2.0 flow are captured in detail.

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