COMPARISON BETWEEN CBOS (COLORED BACKGROUND ORIENTED SCHLIEREN) AND CGBOS (COLORED-GRID BACKGROUND ORIENTED SCHLIEREN) FOR SUPERSONIC FLOW

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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 recent years, CBOS (Colored Background Oriented Schlieren) technique using colored random dot pattern for background is developed to improve the performance of conventional BOS technique using monochromatic random dot pattern, and it is applied to various measurements of flow. On the other hand, Colored-Grid Background Oriented Schlieren (CGBOS) technique using colored-grid pattern for background is developed and applied to measurement of supersonic flow field. CGBOS is based on the image processing technique developed for the analysis of finite-fringe interferogram and using color information is based on the ideas of CBOS technique. This paper describes the comparison of the measurement result between CBOS and CGBOS. Measurements of Mach 3.0 flow around a blunt body with a spike were performed for both CBOS and CGBOS at supersonic wind tunnel at ISL with same optical arrangements. The difference is only background and image processing procedure. Detailed analysis between two techniques will be important for the future development of BOS technique.*

1 Introduction

The Background Oriented Schlieren (BOS) technique is based on a patent by Meier [1] and described by Richard [2] and Meier [3]. BOS technique 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 [2]~[5], free flight experiment [5], free jet [5], [6], rotor blade tip vortex of full-scale helicopter [7], etc. The sensitivity and accuracy of BOS is examined by Goldhahn and Seume [6]. Recently Venkatakrishnan and Suriyanarayanan reported precise measurement of 3D density field of separated flow by BOS [8]. 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 is still important for the various researches and it employs many optical elements - pinhole, concave mirror, knife-edge or color filter, camera...etc. On the other hand BOS requires only a background and a digital still camera and it can realize the quantitative measurement of density. Figure 1 shows optical setup for BOS technique [5]. 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 [4]. The relation between density ρ and refractive index n is given by the Gladstone-Dale equation expressed as equation 2 where K 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.

The random dot patterns are generally used as a background image and the image displacement is calculated by cross-correlation method. Natural background is also applied to the outdoor experiments [9]. BOS has the potential to break many limitations with the conventional schlieren measurements, e.g. restriction on the size of experiments. For the indoor laboratory test, using random dot background and Particle Image Velocimetry (PIV) analysis to calculate displacements of background is becoming the general approach of BOS technique. In recent years, Colored Background Oriented Schlieren (CBOS) technique using colored random dot pattern for background is developed to improve the performance of conventional BOS technique using monochromatic random dot pattern, and it is applied to various measurements of flow [5, 10]. Colored Grid Background Oriented Schlieren (CGBOS) technique using colored-grid background and displacements is measured by finite-fringe analysis is also proposed and succeeds to reconstruct the density field around an asymmetric object [11, 12]. In this paper the comparison between CBOS and CGBOS technique for the same experiment is presented.

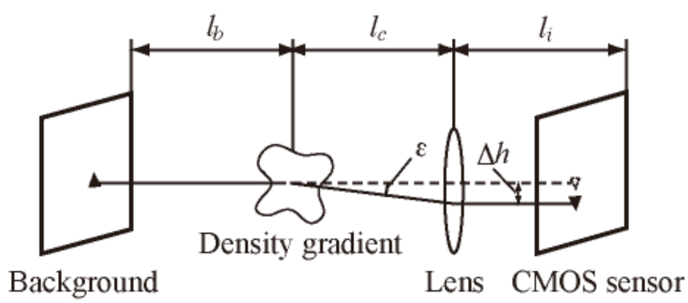

Fig. 1 Optical setup of BOS

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

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

2 CBOS and CGBOS technique

The CBOS technique using colored random dot pattern for background is developed to improve the performance of conventional BOS technique using monochromatic random dot pattern, and it is applied to various measurements of flow [5, 10]. For the CBOS technique primary colors red, green and blue are used to generate the colored background. A typical colored background image is shown in Fig. 2. The displacement of background is obtained from 8 elementary dot patterns – primary red, green and blue dots, all secondary colors, dots containing red, green and blue, and uncolored areas (black dots) to increase the accuracy and spatial resolution. The displacement of each dot patterns is separately calculated by comparison between with flow and without flow images with cross-correlation algorithm commonly used in PIV technique. In order to increase the accuracy of the measurement, a gliding interrogation window is employed. The detail description of CBOS technique can be found in Ref. 5 and 10.

On the other hand, horizontal stripe was employed for background image in ‘synthetic schlieren’ [13], [14]. Dalzeil et al applied synthetic schlieren to measure the gradient of the perturbation density by line refractometry using horizontal lines, dot tracking refractmetry using regular array of dots, and pattern matching refractmetry using randomized array of dots for background [13]. Onu et al adapted synthetic schlieren to measure the vertical amplitude of axisymmetric internal waves by using horizontal lines for background [14]. They also obtained internal wave amplitude in plane of interest with inverse tomographic technique. In these reports, the displacement of line pattern was calculated by taking intensity change between with flow image and without flow image in contrast to calculating the center position of lines directly with finite-fringe analysis method developed for Laser Interferometric Computed Tomography (LICT) technique. LICT technique have been applied to the measurement of three-dimensional (3-D) unsteady and high-speed flow field behind discharging shock waves and succeeded to elucidate various flow phenomena [15]~[18]. 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 previous study [15]~[18]. In this method the center of each fringe is calculated, then the displacement of fringe pattern at designated position is calculated to obtain the projection data of density information. 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.

The CGBOS technique is based on the image processing developed for the finite-fringe analysis mentioned above. In this report, colored background is composed of blue and red stripes. The blue stripe is used for horizontal stripe and red stripe for vertical. Captured CGBOS image can be separated into blue (horizontal) and red (vertical) stripe image by color information. The distortion of background image in vertical and horizontal direction is obtained from horizontal blue-stripe and vertical red-stripe separately. Decomposition of projected image using color information is based on the ideas of CBOS technique. For CGBOS technique, displacement of separated stripe pattern is obtained as follows; firstly a reference image is recorded at rest before or after the experiment. Secondly, test image containing distortion of background is recorded thorough the flow. The center position of every stripe in reference and test image is calculated by finite-fringe analysis approach, and then displacement of background is obtained by comparing the position of stripes between two images.

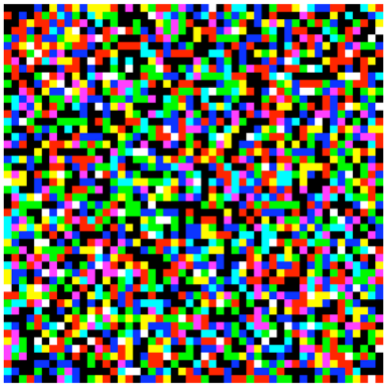

Fig. 2 Colored background image

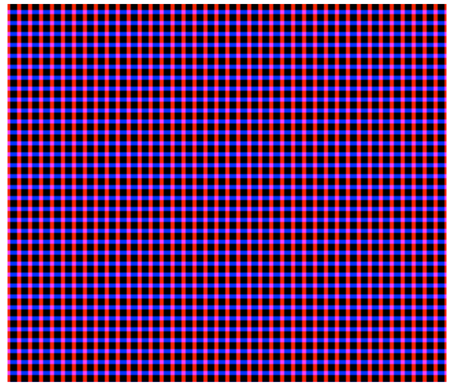

Fig. 3 Colored-grid background image

3 Experiments

The experiments were carried out in the 0.2 m x 0.2 m supersonic blow-down wind tunnel of ISL. The test model is a spike-tipped body as shown in Fig. 4 and it has a cylindrical center body (40 mm in diameter) and a hemispherical nose equipped with concave shaped spike. Freestream Mach number is 3.0 and Reynolds number based on the model diameter is 2.7 x 10^6. The CBOS and CGBOS image are recorded with a digital still camera (Cannon EOS 1 Ds Mark II) with 4992 × 3328 pixels CMOS censor. The experimental setup is shown in Fig. 5, distance l_b and l_c are set to 167 mm and 195 mm. The focal length of camera f is 50 mm and the aperture is set to smallest value 1/22 to increase the depth of focus. The background is illuminated by a flush lamp for duration of 100 μs. For a comparison, CBOS image and CGBOS image are taken with completely same experimental condition. The difference is background image and image analysis method.

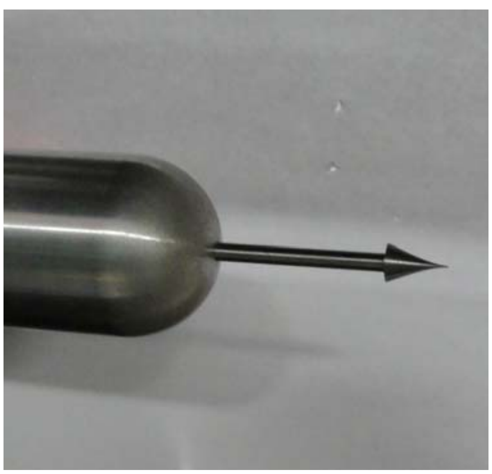

Fig. 4 Spike-tipped body

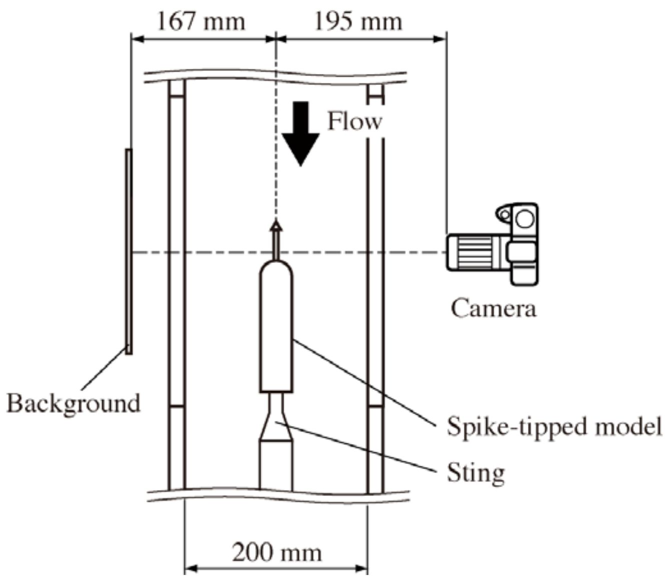

Fig. 5 Experimental setup for CBOS and CGBOS

4 Results

The resultant images of the displacement of background obtained from both CBOS and CGBOS technique are shown in Fig. 6 and 7. An interrogation window of 32 x 32 pixels is used for CBOS measurement and no interrogation window is used for CGBOS because the center position of stripe pattern is measured directly. Shock wave in front of concave spike, expansion waves and bow shock can be recognized form these images. A good agreement can be observed between both techniques. From vertical displacement of CGBOS it can be clearly seen that bow shock is detached from the hemisphere and shock wave from concave spike is slightly curved. From CBOS result, shock wave

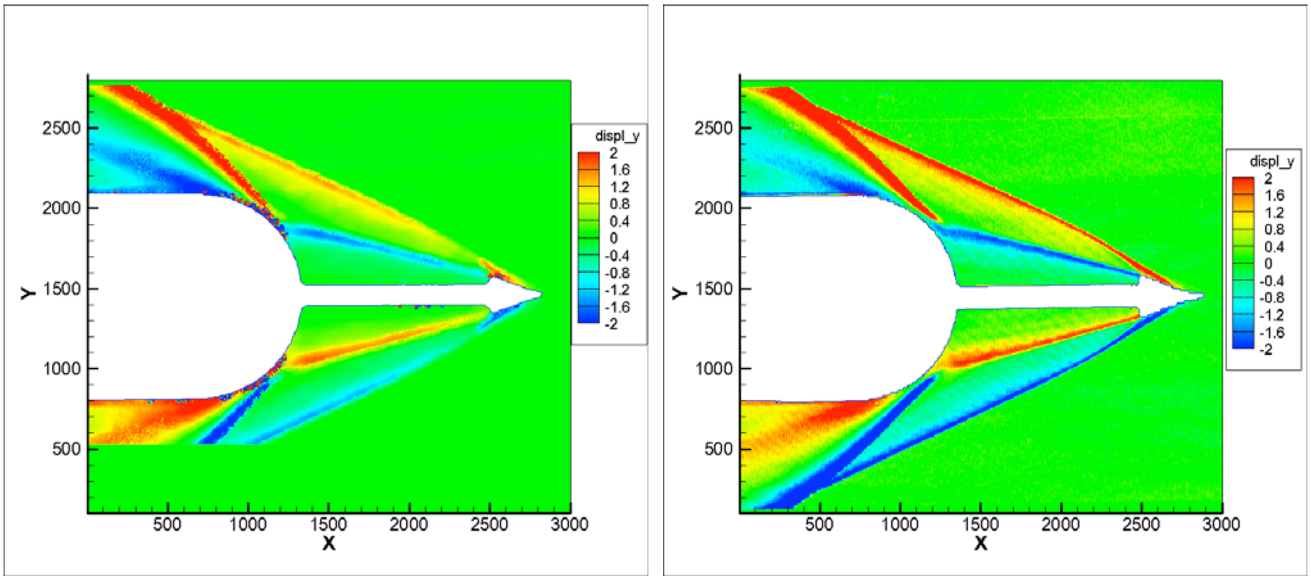

Fig. 6 Vertical displacement in pixels obtianed by CBOS (left) and CGBOS (right)

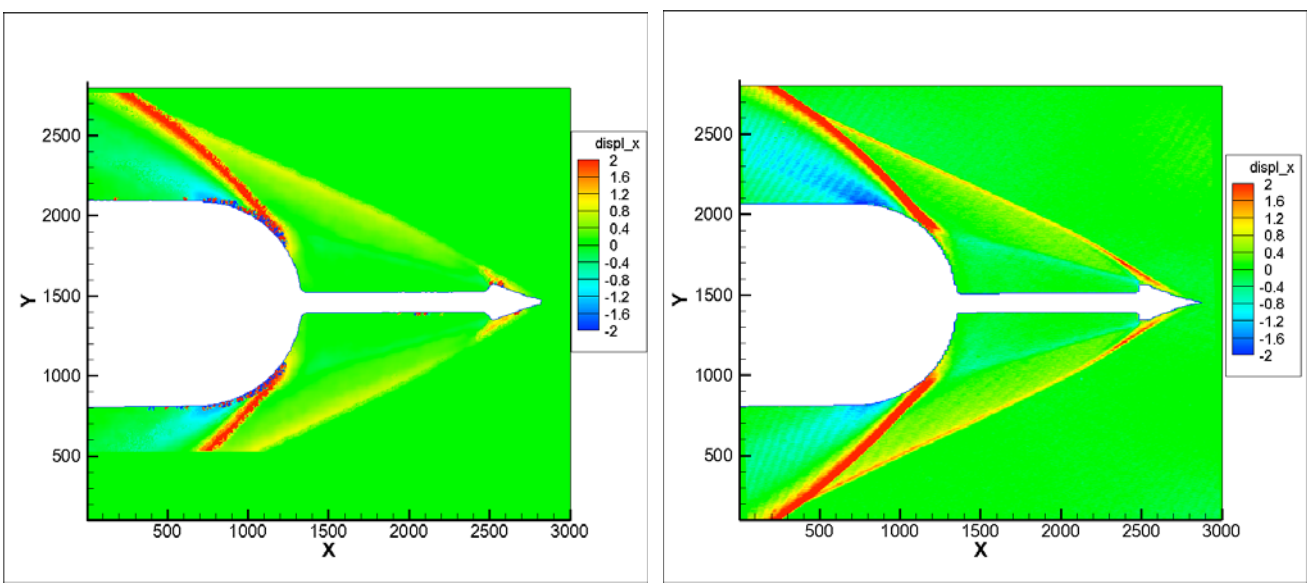

Fig. 7 Horizontal displacement in pixels obtained by CBOS (left) and CGBOS (right)

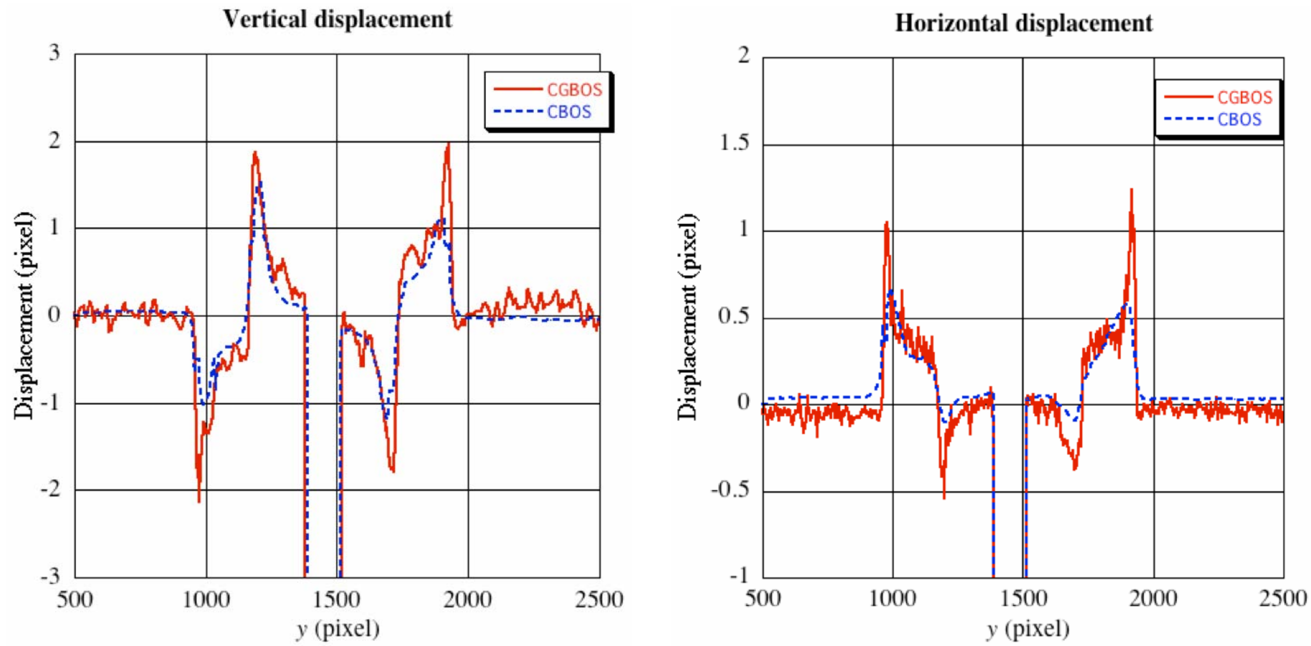

Fig. 8 Plot of hoizontal and vertical displacements (on x = 2000 pixel in Fig. 6 and 7)

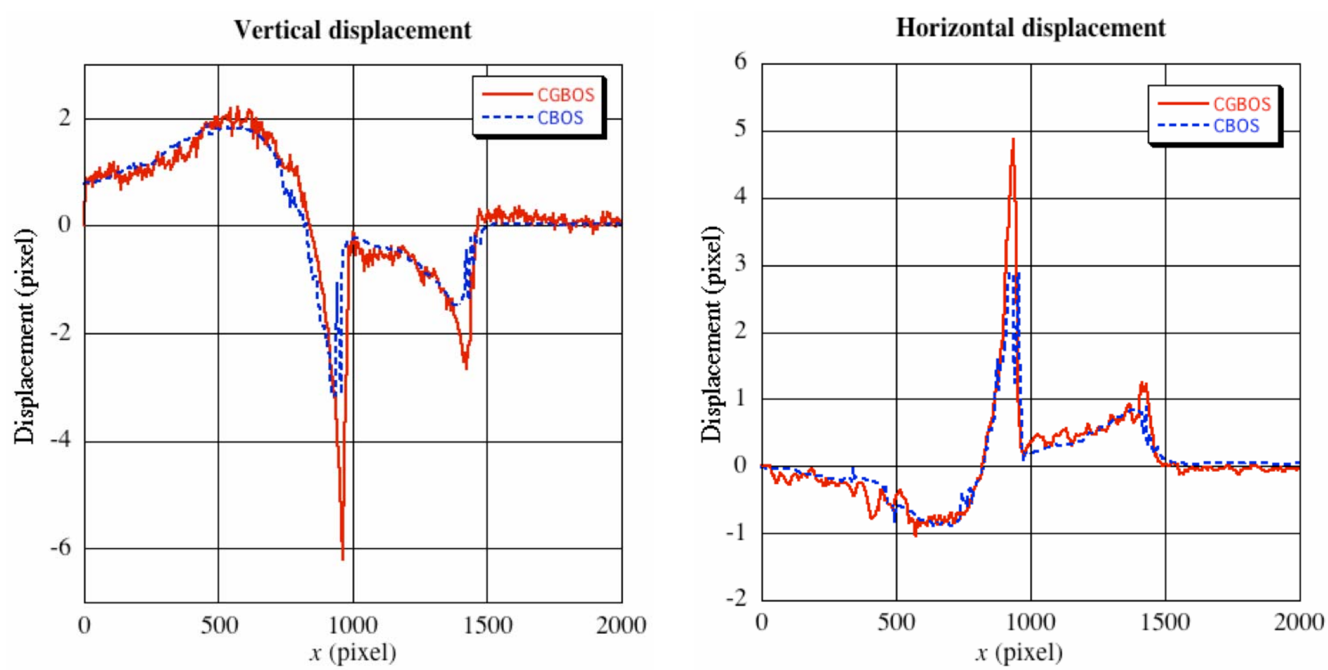

Fig. 9 Plot of hoizontal and vertical displacements (on y = 700 pixel in Fig. 6 and 7)

from concave spike is partially disappeared and some noises can be observed around a body. This can be improved by applying smaller interrogation window for correlation. It can also be recognized that shock wave is continuous and slightly curved in CGBOS result while it is partially disappeared in CBOS result. For detailed comparison plots of obtained displacements with both techniques are shown in Fig. 8 and 9. Displacements on the position of x = 2000 pixel in Fig. 6 and 7 are shown in Fig. 8 and on the position of y = 700 pixel in Fig. 6 and 7 are shown in Fig. 9. A very good agreement can be observed in these plots in spite of both techniques employing different approach in post processing. Center positions of all stripes are calculated directly in CGBOS while sub-pixel approach is used in CBOS technique. Strong density gradients corresponding to shock waves and expansion waves are captured more sharply in CGBOS than CBOS result. Displacement data of striped pattern are obtained continuously in the direction of stripes in CGBOS technique, therefore even the strong gradient in short distance is captured.

5 Conclusion

The experiments for CBOS and CGBOS technique are performed in the supersonic wind tunnel at ISL with the same optical arrangement for the detailed comparison between both techniques. A very good agreements in displacement data are obtained nevertheless the displacements of background are measured with different approach. The image displacement is measured with cross-correlation method in CBOS and with direct measurement of the center position of stripes in CGBOS technique. In this report it can be concluded that CGBOS technique achieves higher resolution than CBOS technique. Both techniques have the advantages and disadvantages of course, various improvements can be applied to both techniques to obtain higher resolution and accuracy.

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