INCREASE OF ACCURAY FOR CBOS BY BACKGROUND PROJECTION

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ABSTRACT The improved Background Oriented Schlieren technique CBOS (Colored Background Oriented Schlieren) is described and applied to determine the flow field around different test models. The technique allows the measurement of the light deflection caused by density gradients in a compressible flow. For this purpose the distortion of the image of a background pattern observed through the flow is used. In order to increase the performance of the conventional Background Oriented Schlieren (BOS) technique, the monochromatic background is replaced by a colored dot pattern. The different colors are treated separately using suitable correlation algorithms. Therefore, the precision and the spatial resolution can be highly increased. In order to evaluate the distortion of the image of the background with a correlation method it is important to focus on the background. Especially for big wind tunnels the distance between the flow field, which has to be observed, and the background is greater than the depth of field of the camera. A solution to overcome this problem is to project the background close to the wind tunnel model. The CBOS technique is explained and applied to the measurement of the flow field around an asymmetric mounted spike-body configuration in a supersonic wind tunnel.

1 Introduction

The determination of the density distribution is important for the investigation of compressible flows. For this purpose the schlieren method, introduced by A. Toepler in 1864, is currently used [1]. The schlieren method transforms the phase variation of light passing through a phase object into an intensity variation. In the seventies and eighties new techniques such as density speckle photography appeared, in which the deflection of the light could be measured directly [2-4]. Later an improved version of density speckle photography was used for this purpose [5, 6].
The Background Oriented Schlieren (BOS) technique is based on a patent held by Meier [7] and more precisely described by Raffel [8-10]. In order to measure the light deflection caused by density gradients in a compressible flow, the BOS technique uses the distortion of a background image. Tiny, randomly distributed dots on a flat plate are used as

a background. The recording has to be performed as follows: first a reference image is generated by recording the background pattern observed through the air at rest before or after the experiment. Secondly, an additional exposure through the flow under investigation is taken. Local changes in the refraction index of the moving compressible test medium lead to an optically displaced image of the background pattern. The resulting images of both exposures can then be evaluated by correlation methods, leading to the local displacements and thus to the deviations of the rays. This paper describes how to improve the accuracy and spatial resolution of the BOS technique by using a background pattern of colored dots (CBOS technique) and suitable correlation algorithms as well as post-treatment methods.
Furthermore, the rays deviations in a given observation direction are a projection of the (integral of the gradient of) the density in the flow. Therefore, a tomography reconstruction method is used to reconstruct the density field in symmetrical as well as completely three-dimensional compressible flows. Then, comparisons between the reconstructions of the density field obtained by applying suitable tomographic techniques and numerical simulations are made.

2 Background Oriented Schlieren Technique

2.1 Principle of the BOS technique

The principle of the BOS technique is based on the measurement of the deviation of the light passing through a phase object. Indeed, the BOS technique uses the distortion of a background image for detecting the changes in density gradients. Due to the empirical law of Gladstone-Dale, the density can directly be related to the refractive index:

$$\frac{n-1}{\rho} = const = G(\lambda) \quad \text{with} \tag{1}$$

$$G(\lambda) = 2{,}2244 \cdot 10^{-4}\,\frac{m^3}{kg} \cdot \left(1 + \left(\frac{6{,}7132 \cdot 10^{-8}\,m}{\lambda}\right)^2 + \left(\frac{1{,}0686 \cdot 10^{-7}\,m}{\lambda}\right)\right)$$

where n represents the refractive index which is defined as the ratio of the speed of light in vacuum to the speed of light in the optical medium; ρ stands for the density of the medium, G denotes the Gladstone-Dale constant which depends on the characteristics of the gas and λ represents the wavelength of the light. As the changes in the Gladstone-Dale constant in the visible spectral range are very small, the constant is set at the value $G(\overline{\lambda}) = 2.26 \times 10^{-4}\ \mathrm{m^3/kg}$ for an average wavelength of $\overline{\lambda} \approx 550\ \mathrm{nm}$.
The distortion χ can be expressed by integrating the local index gradients along the light path:

$$\chi(x,y) = \frac{f\,Z_B}{Z_C + Z_B - f} \int_{\Delta_z} \frac{1}{n_0} \frac{\delta n}{\delta r(x,y)}\,dz \tag{2}$$

where z represents the coordinate along the light path, f the focal length of the camera lens, Z_C the distance from the camera to the phase object and Z_B the distance from the phase object to the background image, as shown in fig. 1. Now the Gladstone-Dale relation allows conclusions to be drawn from the two-dimensional distortion $\chi(x,y)$ in order to determine the density gradients $\delta\rho/\delta x$ and $\delta\rho/\delta y$ in the horizontal and vertical directions, respectively [8-10].
The CBOS technique normally uses a computer-generated random dot pattern which is placed in the background of the test volume. This pattern has to possess a high spatial frequency that can be imaged with a high contrast. It usually consists of tiny, randomly distributed dots. Earlier studies [11] pointed out that the dot pattern for an optimized evaluation should cover from 30% to 70% of the surface of the background image. Since the primary colors red, green and blue (according to the RGB color model) can easily be detected by the CMOS chip of commercial digital cameras, these colors are used to generate the colored back-ground for the CBOS technique.

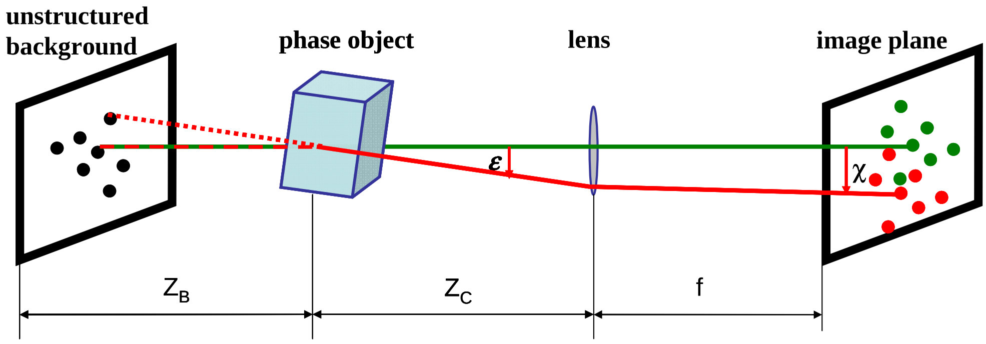


Fig. 1 Optical setup for the BOS technique

2.2 Correlation Algorithm: Determination of the Displacement Vectors

For the determination of the displacement vectors between the patterns of two interrogation windows the cross-correlation method as already applied in the PIV technique, is used [12 - 14]. As the chosen correlation technique is based on the fast Fourier transformations (FFT) which assumes the periodicity of the data sample, a correction for nonperiodic data samples has to be applied in order to avoid artifacts. Therefore, two correction approaches are proposed:
the linear weight kernel is applied to the result of the cross correlation [11, 12]

$$\omega(i, j) = \left(1 - \frac{i-1}{M}\right)\left(1 - \frac{j-1}{N}\right), \tag{3}$$

where M and N denote the dimensions of the interrogation windows.
the gaussian weight kernel is applied directly to the grey values of one interrogation window [11, 12].

$$\omega(i, j) = \exp\left(-4\left(\frac{\left(i - \frac{M}{2}\right)^2}{\left(\frac{M}{2}\right)^2} + \frac{\left(j - \frac{N}{2}\right)^2}{\left(\frac{N}{2}\right)^2}\right)\right) \tag{4}$$

In order to estimate the displacement vector, the position of the maximum value in the correlation result is searched for. Therefore, only integer displacements between the two correlated interrogation windows can be assessed. In order to increase the accuracy of the displacements, the neighboring points are taken into consideration. Therefore, between three different approaches to determine the core peaks due to the surrounding gray values $\hat{R}$ can be choosen [8, 11, 12]:

- linear-fit estimator : $\Delta x_l = \dfrac{\hat{R}_{+1} - \hat{R}_{-1}}{\hat{R}_{-1} + \hat{R}_0 + \hat{R}_{+1}}$ (5)

- parabolic-fit estimator: $\Delta x_p = \dfrac{\hat{R}_{-1} - \hat{R}_{+1}}{2\left(\hat{R}_{-1} - 2\hat{R}_0 + \hat{R}_{+1}\right)}$ (6)

- gaussian-fit estimator: $\Delta x_g = \dfrac{\ln\left(\hat{R}_{-1}\right) - \ln\left(\hat{R}_{+1}\right)}{2\left(\ln\left(\hat{R}_{-1}\right) + \ln\left(\hat{R}_{+1}\right) - 2\ln\left(\hat{R}_0\right)\right)}$ (7)

3 Wind tunnel and test model

The experiment is carried out in the 0.2 m × 0.2 m supersonic blow-down wind tunnel S20 of ISL with a freestream Mach number of 3 and a temperature at rest T_0 = 293 K. The Reynolds number Re_D based on the model diameter (D = 40 mm) is 2.7 × 10^6 and the tunnel freestream static pressure *p* is 190 hPa. The test model used for this investigation is a spike-tipped body equipped with a conical tip (fig. 2).

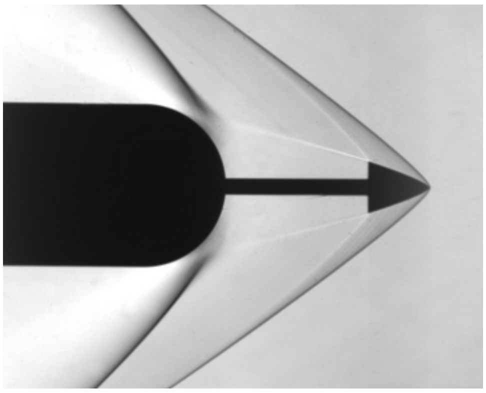


Fig. 2 Schlieren photo from the spike-tipped wind tunnel model

4 Projected Background

Especially for big wind tunnels the distance between the flow field, which has to be observed, and the background is greater than the depth of field of the camera [17, 19, 20]. Figures 3a and 3b show clearly, that even in the best possible case the depth of field do not exceed 25 cm. A solution to overcome this problem is to project the background close to the wind tunnel model. Therefore a slide projector is used in order to project the image of the slide with the background near the test model.

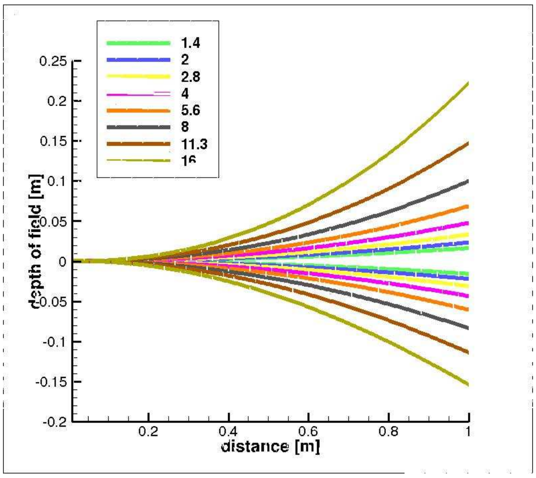


Fig. 3a Depth of field for a typical 50 mm objective for different aperture settings

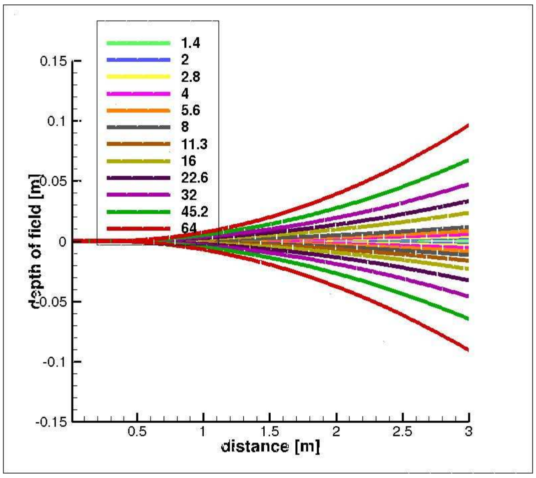


Fig. 3b Depth of field for a typical 400 mm objective for different aperture settings

In figures 4a, 5a and 6a the optical set-up is shown. The camera is equipped with an objective with a focal length of 50 mm. The pictures are taken with the smallest aperture, here 1/16. The distance Z_B between the background and the model varies between +20 mm and -20 mm, the distance Z_C between the model and the lens of the camera is equal to 250 mm. The background is illuminated by a flash lamp, this time for a duration of 150 µs. In figures 4b, 5b and 6b the results for the vertical displacements are shown. In accordance with the relation (2) we have for a projection of the background image close to the test model (fig. 5a) the smallest displacements (fig. 5b). It could be remarked, that for the figures 4b and 6b the sign of the vertical displacements changes.

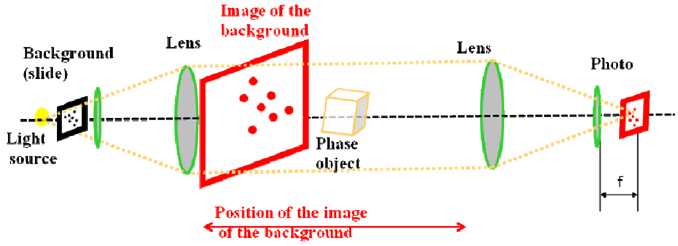


Fig. 4a Optical set-up for CBOS measurements with projected background before the wind tunnel model.

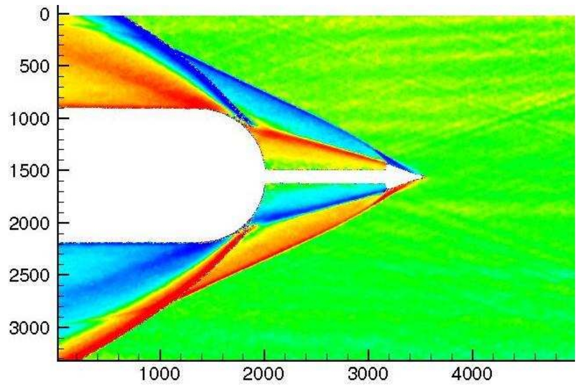


Fig. 4b Values for the vertical displacements for the optical set-up in figure 4a.

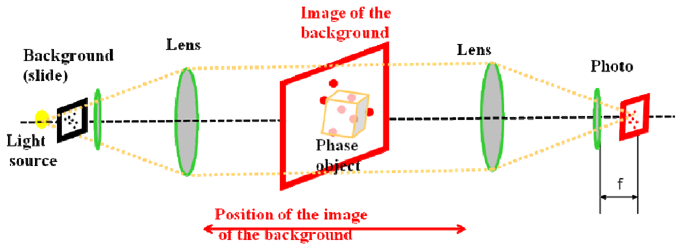


Fig. 5a Optical set-up for CBOS measurements with projected background near the wind tunnel model.

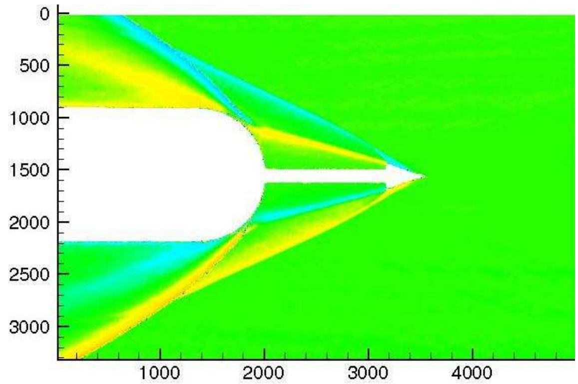


Fig. 5b Values for the vertical displacements for the optical set-up in figure 5a.

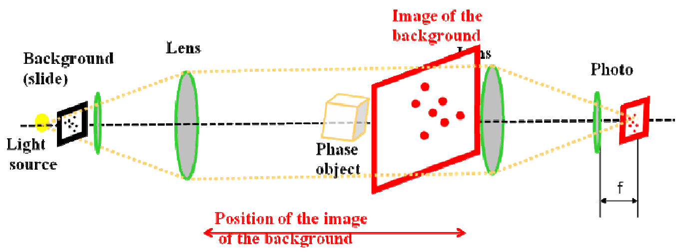


Fig. 6a Optical set-up for CBOS measurements with projected background behind the wind tunnel model.

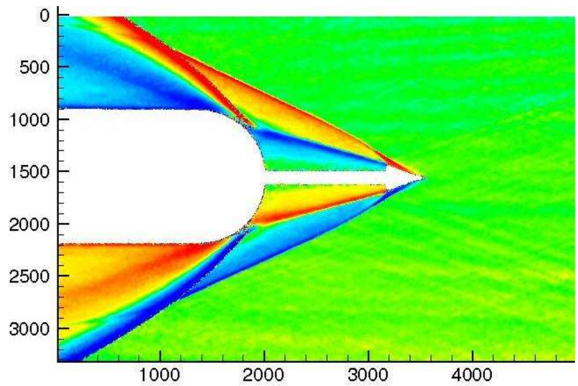
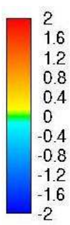
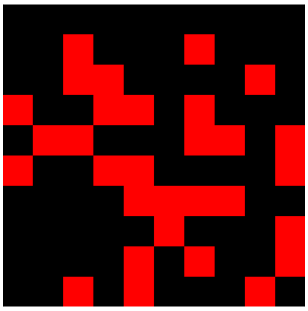


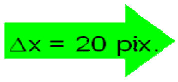
Fig. 6b Values for the vertical displacements for the optical set-up in figure 6a.



5 Shift of the different dot patterns in the background

Nevertheless we still have to treat the problem of the blurred image of the dots in the shock region [17, 21]. One approach to overcome this problem is to shift the red dot pattern (fig. 7a) in horizontal direction and change the color of the dots in green (fig. 7b). In the next step the red dot pattern is shifted of the same amount but this time in vertical direction and colored in blue (fig. 7c). The superimposition of the different dot pattern leads to the new colored background image (fig. 7d).





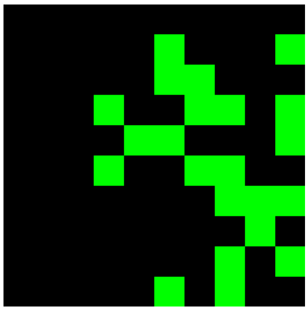
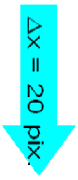
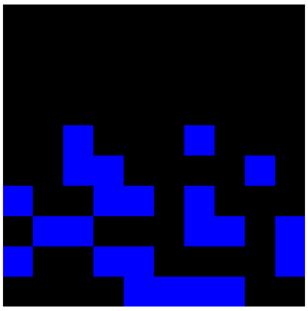


Fig. 7a Original red dot pattern

Fig. 7b Original dot pattern shifted to the left and colored in green





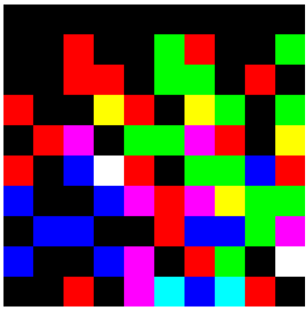


Fig. 7c Original dot pattern shifted to the left and colored in blue

Fig. 7d Final colored dot pattern

Fig. 7 Construction of the background image based on the shift of the red dot pattern

In figure 8a the horizontal and in figure 9a the vertical displacements from a CBOS correlation between the reference image and the measuring image are shown. Figure 8b shows the horizontal displacements between the red and the green dot pattern. Figure 9b shows the vertical displacements related to correlation between the red and the blue dot pattern. For the results in figure 8b and 9b only the measuring image is needed. It could be remarked, that the representation of the shock is very sharp. The displacements in figures 8b and 9b correspond to the derivations of the result in figure 8a and 9a. Figure 10b corresponds to a classical shadowgraph image.

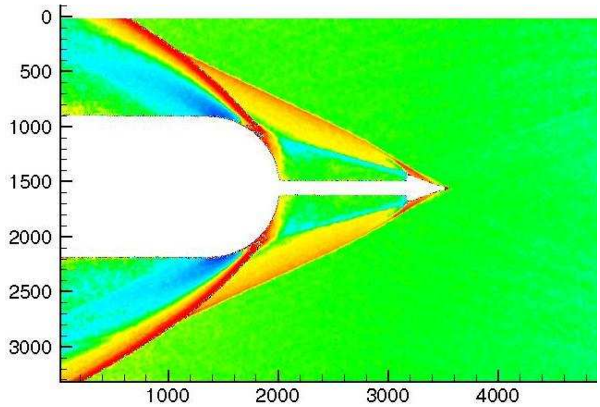


Fig. 8a Horizontal displacements determined from correlation between the reference image and the measuring image.

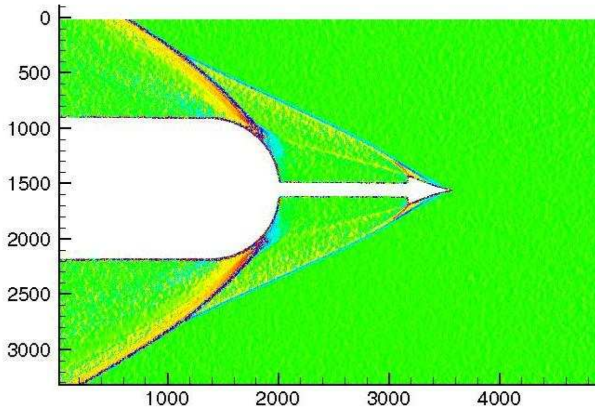
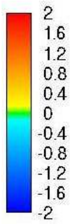


Fig. 8b Horizontal displacements determined from correlation between the red and green dot pattern.



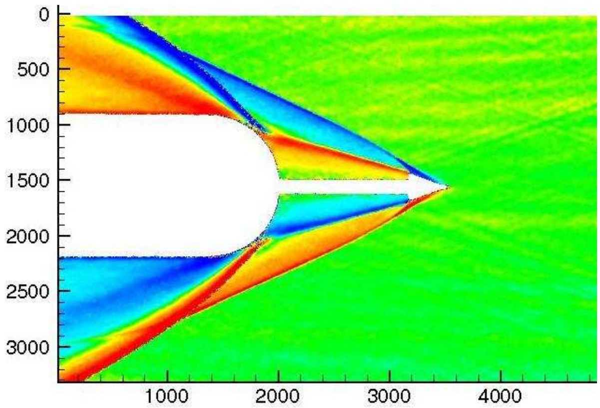


Fig. 9a Vertical displacements determined from correlation between the reference image and the measuring image.

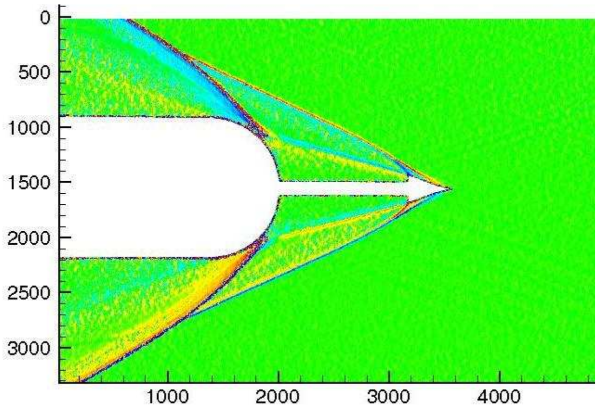


Fig. 9b Vertical displacements determined from correlation between the red and blue dot pattern.

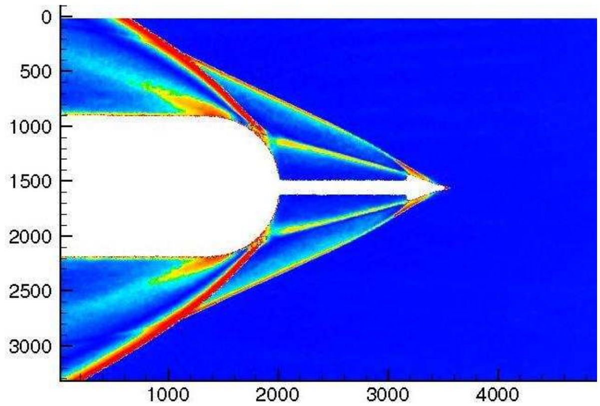
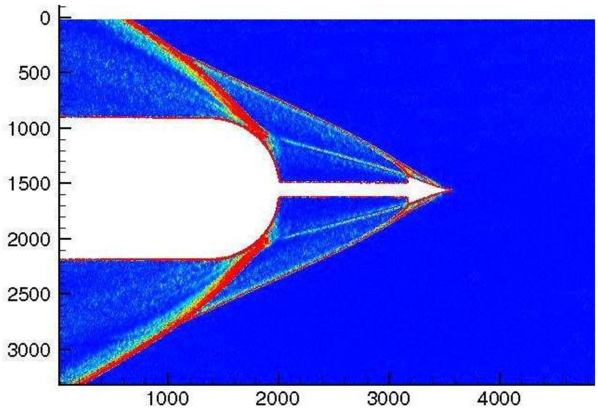


Fig. 10a Absolute value for the displacements determined from correlation between the reference image and the measuring image.



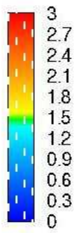


Fig. 10b Absolute value for the displacements in figures 9a and 9b (shadowgraph).

6 Conclusions

The Background Oriented Schlieren technique is a promising tool for the analysis of a flow with density gradients. In comparison with traditional methods, like the schlieren method, differential interferometry, etc., the BOS technique is acknowledged for its simple optical setup and easy handling. In the case of the CBOS technique and due to the colored background, eight different dot patterns can be recorded simultaneously with one camera. The use of gliding interrogation windows as well as the post-treatment by applying weight kernels to the correlation algorithm and special fit-estimators allow the spatial resolution and the accuracy of the method to be increased. For the application in big wind tunnels the projected background approach is introduced. In order to get a sharper representation of the shock structures the new colored background with the shifted dot pattern system is proven.

References

1. Settles G. S., *Schlieren and Shadowgraph Techniques*, Springer, Berlin Heidelberg New York, 2001, pp. 1-24.
2. Fomin N.A. Speckle photography for fluid mechanics measurements. Springer, Berlin, 1998
3. Debrus S., Francon M., Grover CP, May M., Robin ML, Ground glass differential interferometer, *Applied Optics, 11*, p. 853, 1972.
4. Köpf U., Application of speckling for measuring the deflection of laser light by phase objects, *Opt. Commun, 5*, pp 347-350, 1972.
5. Wernekink U., Merzkirch W., Speckle photography of spatially extended refractive-index fields, *Applied Optics, 26*, pp 31-32, 1987.
6. Niessen R. Schäfer H. J., Merzkirch W., Measurement of length scales in the turbulent wake behind a cylindrical body at supersonic flow velocities, *IUTAM Symposium "Eddy Structure Identification in Free Turbulent Shear Flows*", Poitiers, France, ISL-CO 235/92, 1992.
7. Meier G. E. A., *Hintergrund-Schlierenverfahren*, Deutsche Patentanmeldung, DE 19942856 A1, 1999.
8. Raffel M., Optische Untersuchungen in technischen Strömungen unter besonderer Berücksichtigung eines Verfahrens zur Detektion von Dichtegradienten, Habilitationsschrift, Tech. Univ. Clausthal, 2001.
9. Richard, H. Raffel M. Principle and Application of the Background Oriented Schlieren (BOS) method, Meas. Sci. Technol., 2001, **12** (9), pp 1576-1587
10. Augenstein E., Leopold F., Richard H., Raffel M., Schlieren Techniques in Comparison: Background Oriented Scattering versus Visualization with Holographic Filters, *4th Int. Symposium on Particle Image Velocimetry*, Göttingen, Germany, Paper 1191, 2001.
11. Westerweel J., Digital Particle Image Velocimetry, Theory and Application, *Tech. Univ. Delft, Delft University Press*, 1993.
12. Gui L., Merzkirch W., Fei R., A digital mask technique for reducing the bias error of correlation-based PIV interrogation algorithms, *Experiments in Fluid 29*, Springer-Verlag, 2000.
13. Klatt D., Entwicklung von Messtechniken zur Vermessung der Lichtablenkung an Dichtegradienten in kompressiblen Strömungen mit Hilfe der CBOS-Technik, Diplomarbeit, 2009, ISL, France.
14. Leopold F., Simon J., Gruppi D., Schäfer H. J., Recent improvements of the background oriented schlieren technique (BOS) by using a colored background, *12th International Symposium on Flow Visualization*, Göttingen, Germany, 2006.
15. Leopold F., Sourgen F., Klatt D., Jagusinski F., *Reconstruction de la masse volumique à partir des images CBOS*, ISL-PU 602/2010.
16. Klinge F., Riethmuller M. L., Local density information obtained by means of the Background Oriented Schlieren (BOS) method, *11th International Symposium on Application of Laser Techniques to Fluid Mechanics*, Lisbon, Portugal, 2002.
17. Leopold F. The Application of the Colored Background Oriented Schlieren Technique (CBOS) to Free-Flight and In-Flight Measurements, Journal of Flow Visualization and Image Processing, 2009, **16** (4) p. 26 ff
18. Sourgen F., Leopold F., Klatt D., Jagusinski F., Reconstruction of the density field using the Colored Background Oriented Schlieren Technique, Optics in Lasers and Engineering, online 10.1016/j.optlaseng.2011.07.012, Volume 50, No. 1, pp. 29-38, 2012.
19. Ota M., Hamada K., Kato H., Maeno K., Computed-tomographic density measurement of supersonic flow field by Colored-Grid Background Oriented Schlieren (CGBOS) technique, *Meas. Sci. Technol.*, 2011, **22**, 104011
20. Ota M., Hamada K., Maeno K., Three-dimensional density measurement of supersonic flow by Colored Grid Background Oriented Schlieren (CGBOS) technique, *Proc. 13th International Symposium on Flow Visualization*, Exco Daegu, Korea, 2010.
21. Ota M., Inage T., Maeno K., An extension of laser-interferometric CT measurement to unsteady shock waves and 3D flow around a columnar object, *Flow Meas. Instrum.*, 2007, **18**, 295-300.