

Background oriented Schlieren technique – sensitivity, accuracy, resolution and application to a three-dimensional density field

Erik Goldhahn¹, Jörg Seume²

1: Institute of Turbomachinery and Fluid-Dynamics, University of Hannover, Germany, goldhahn@tfd.uni-hannover.de

2: Institute of Turbomachinery and Fluid-Dynamics, University of Hannover, Germany, seume@tfd.uni-hannover.de

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1. Introduction

For the complete characterization of isothermal flows, one thermodynamic state variable is needed in addition to the velocity field. In this work the background oriented schlieren method (BOS) was used together with a tomographic reconstruction algorithm to determine the 3D density field of a complex 3D flow. In advance to the measurements the sensitivity, accuracy and resolution of the BOS method were investigated.

2. The BOS method

A BOS set-up mainly consists of a camera, a computer to take and evaluate the images, and a background with a random dot pattern. The BOS method is, as all methods in the group of schlieren techniques are, sensitive to those components of the first spatial derivative of the index of refraction (n), which are perpendicular to the line of sight (l). The integral of these components can be determined with the BOS method using Equation 1 (φ_{in} is the angle between $\text{grad}(n)$ and l , ε is the deflection angle). For gases with $n \approx 1$, this equation can be used in a simplified version (Equation 2). The index of refraction and the density are connected by the Gladstone Dale relation. These integrals are also referred to as projections.

$$\varepsilon \approx \tan(\varepsilon) = \sin(\varphi_{in}) \cdot \int_l \frac{1}{n(x, y, z)} \text{grad}\{n(x, y, z)\} dl \quad (1)$$

$$\varepsilon \approx \tan(\varepsilon) = \sin(\varphi_{in}) \cdot \int_l \text{grad}\{n(x, y, z)\} dl \quad (2)$$

3. Sensitivity, accuracy and resolution of the BOS method

With BOS, the apparent shift of a background pattern due to the refraction of light by a density gradient field is determined. Using the geometric dimensions of the BOS set-up, the deflection angle (ε) in Equation 3 can be calculated from that shift. It is related to the line of sight integral over the index of refraction gradients. Therefore the sensitivity question leads to the question for the smallest detectable integral in Equation 2. Assuming, that the deflection of the light rays is concentrated to one point in space one can get a relation as in Equation 3.

$$\varepsilon \approx \tan(\varepsilon) = \sin(\varphi_{in}) \cdot \int_l \text{grad}\{n(x, y, z)\} dl = \frac{(1+l/m) \cdot v_{Px} \left(\frac{g-f}{g \cdot f} \right)}{l/m - \left(v_{Px} \left(\frac{g-f}{g \cdot f} \right) \right)^2} \quad (3)$$

It shows that the sensitivity mainly depends on the focal length of the Camera lens (f), the position of the density object between Camera and background (m/l) and the smallest detectable pixel shift (v_{Px}) whereas the overall length (g) of the set-up has only minor influence.

The accuracy was assessed by investigating the virtual 2D density field of thermally stable stratified air. The field was determined by means of temperature sensors and BOS-measurements simultaneously. The comparison of the results showed good agreement even for very low values of the density gradient.

A definition of resolution can be found if one decomposes a projection into its harmonic components. Then the resolution of a BOS set-up is the highest spatial frequency which can still be observed. It can be shown that only the mean value of the shift in a projection is measured correctly and that there is even a phase-shift of π for certain spatial wavelengths. But it is possible to reconstruct the true values of the projection data since the transfer function is known.

4. Density measurement at a double free jet of air

The density distribution of a double free jet of air was determined. For that purpose the projections of the density gradient field was captured in 36 directions with one camera. The mean values of each measurement direction were used to reconstruct the 3D density field (Figure 1). The reconstructed 3D density field shows the typical diamond structure of the density distribution in under-expanded free jets with good resolution.

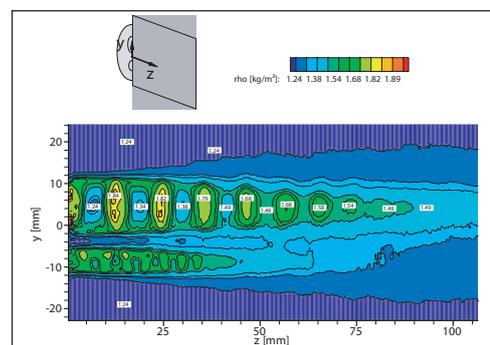


Fig. 1 Center slice at $x=0$ mm, y, z

5. Conclusions

The present work quantifies accuracy, resolution, and sensitivity of the BOS method and shows its applicability to a complex 3D flow. For unsteady flows, however, the next step must be simultaneous measurements by several cameras.