Measurements of density fields in micro nozzle plumes in vacuum by using an enhanced tomographic Background Oriented Schlieren (BOS) technique

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Abstract

The measuring principle of BOS is based on light ray deflection along density gradients normal to the lines of sight. For high precision BOS measurements in a small field of view around a micro nozzle exit a long-distance microscope (LDM), a high resolution CCD camera and evaluation software based on cross-correlation for determining displacement vector fields have been used in the propulsion laboratory of ESA-ESTEC in Noordwijk. The density distribution inside a micro nozzle free jet of nitrogen into a vacuum chamber has been investigated using optical tomography for measurement data achieved with BOS.

Keywords: Optical field measurements, BOS, cross-correlation, tomography, density fields

1. Introduction

The development and test of a transportable and modular μBOS system for application in measurement projects aiming at the determination of density fields in a plume of a micro nozzle in vacuum chambers will be described in this paper. In a first step hardware components of the μBOS system have been assessed and tested in a pre-campaign on the density field in the plume of a micro nozzle in the CCG (Contamination Chamber Göttingen) at various inlet pressure levels p_0. The system consists of an illumination source (*cw*-lamp), several random dot image targets, a relay lens, a long-distance microscope (LDM), a high resolution CCD- camera and evaluation software based on cross-correlation with online-presentation of displacement vectors fields. Instead of fixed random dot patterns illuminated from the background we choose a Digital Mirror Device (DMD) beamer for the final campaign at ESTEC-EPL enabling the possibility of projecting and capturing several hundreds of various random dot images within a few minutes assuming steady flow conditions. Treating vibration effects by image-processing and averaging the cross-correlation results enhances the accuracy of the displacement vector determination by a factor of 100. With a tomographic reconstruction algorithm the calculation of the density fields can be realised from integrating the displacement vector field as determined along different lines of sight. The displacement vector fields are caused by the refractive index changes related to the density gradients present in the investigated flow. The rotational symmetry of the plume allows using the average vector field gained from one viewing direction perpendicular to the flow axis for several simulated viewing directions (here 360) in the tomographic reconstruction process in order to enhance the homogeneity of the calculated density fields.

2. BOS technique – theory and principle

The BOS technique is an optical measurement system to detect density gradients and enables the quantitative determination of density fields [1, 2]. The principle is based on the fact that a light beam passing a density fluctuation is diverted due to the variation in the index of refraction. This deviation is measurable with the following experimental setup:

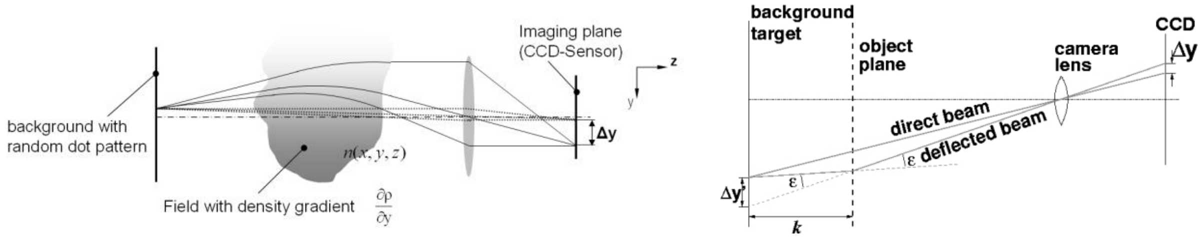

Fig. 1. Working principle of BOS (left) and deflection angle and displacement (right).

The setup consists of three components. These are, as shown in Fig. 1 (top), a background target with a random dot pattern, a light source for the illumination of the background and a high resolution CCD-camera. The measurement is accomplished as follows: First a reference image is generated by recording the background without any density variation. In the second step, an additional image of the background is recorded through the flow under investigation. The random dot pattern is shifted locally due to the density distribution. By means of a correlation method this displacement is computable.

The relation between the deflection angle ε and the apparent displacement $\Delta y'$ is shown in Fig. 1 (bottom) and, since ε is small, it can approximately be written as:

$$\tan(\varepsilon) = \frac{\Delta y'}{k}$$

The relation between the deflection angle ϵ and the index of refraction n on the other hand is given by Merzkirch [3]:

$$\tan(\varepsilon) = \int \frac{1}{n}\frac{\partial n}{\partial y}\,dz$$

To determine the density, the Gladstone-Dale equation can be used:

$$n - 1 = K\rho$$

Where n is the refraction index, ρ the density and K is the Gladstone-Dale constant depending on the wavelength of the incoming light and the properties of the fluid. For the reconstruction of a three dimensional density distribution, the filtered backprojection approach is used [4]. The quality of the reconstruction depends on the number of lines of sight. In the case of a radial symmetrical problem only one line of sight is needed which can be used multiple.

2.1 Spatial resolution contra signal to noise ratio (SNR)

The increase of the distance between background and the flow under investigation leads to a growing magnitude of the displacement vector for the same density gradient object (provided the angle ε is kept constant). As a consequence the SNR rises resulting in an improved quality of the measurement. However, a contrary effect of a bigger distance is the decrease of the spatial resolution. Every point on the background image is the beginning of a cone of light beams passing the camera aperture. Thus, the light of one point passes an area of different density distributions. Hence the deflection on the camera image results from the integrated density gradient of a whole area, depending on the size of the aperture used. For determination of the spatial resolution the correlation window size (*w*) and the diameter of one light beam cone in the object plane (*d*) has to be considered. The cross correlation algorithm calculates one displacement vector for each window size, which means the spatial resolution of the cross correlation algorithm is the window size projected to the object plane (see Fig. 2).

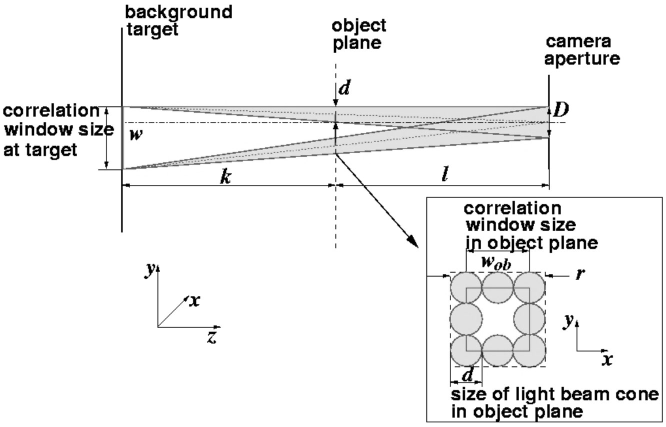

Fig. 2. Spatial resolution considering correlation window and light beam size.

As mentioned before the spatial resolution of the BOS system depends on the aperture of the camera and the distances between object and background k and between object and camera l. Both effects have to be taken into account for the determination of the spatial resolution of the whole system. Each outermost point in the window has a light beam with a diameter d in the object plane. For the spatial resolution applies (see Fig. 2):

$$r = w_{ob} + 2\frac{d}{2} \text{ with } d = \frac{k}{k+l}D$$

Where r is the spatial resolution, w_{ob} is the correlation window size in the object plane and d the diameter of the light beam of the outermost point. With the aperture diameter D and the corresponding distances, d can be calculated easily.

Now the spatial resolution of the BOS system can be written as:

$$r = w_{ob} + \frac{k}{k+l}D$$

3. Set-up, measurements and displacement vector fields

During the BOS measurement campaign of the Astrium 0.5 N thruster plume in the Galileo vacuum tank at ESTEC-EPL an enhanced µBOS measuring system has been combined, consisting of a PCO 1600 CCD- camera, a K2- infinity LDM, a DMD for a synchronized projection of several hundreds of different random dot patterns on a screen and a relay lens for image shifting in order to increase the spatial resolution (see Fig. 3). The flow and background pressure regime have been controlled to be constant during measurement time.

Figure 4 shows an average over 700 displacement vector fields calculated with a cross-correlation multi-grid image deformation scheme with 32^2 pixels interrogation window size and 50 % overlap in step size. The vector field has been measured at the lowest density (gradient) used during this feasibility campaign with 2 mg/sec N_2 mass flow and 8.2×10^{-3} mbar background pressure. It is documented here in order to show the potential of further investigations of even weaker micro thruster plumes with this BOS technique.

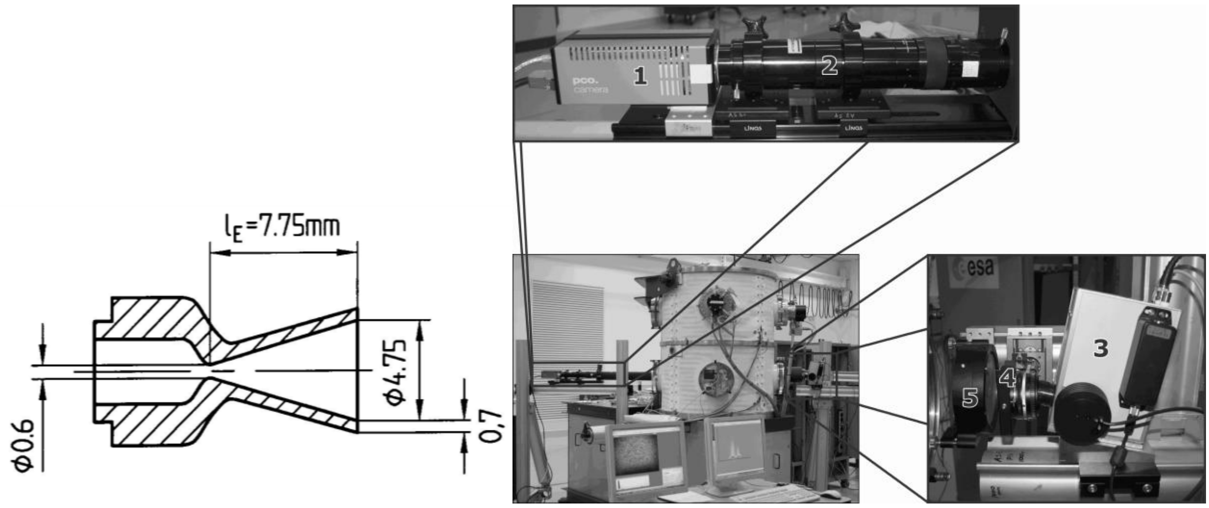

Fig. 3. Astrium 0.5 N monopropellant thruster nozzle (left) and set-up of microBOS system with CCD (1), LDM (2), DMD (3), Screen (4) and relay lens (5) at Galileo vacuum tank of ESTEC-EPL, Noordwijk (right).

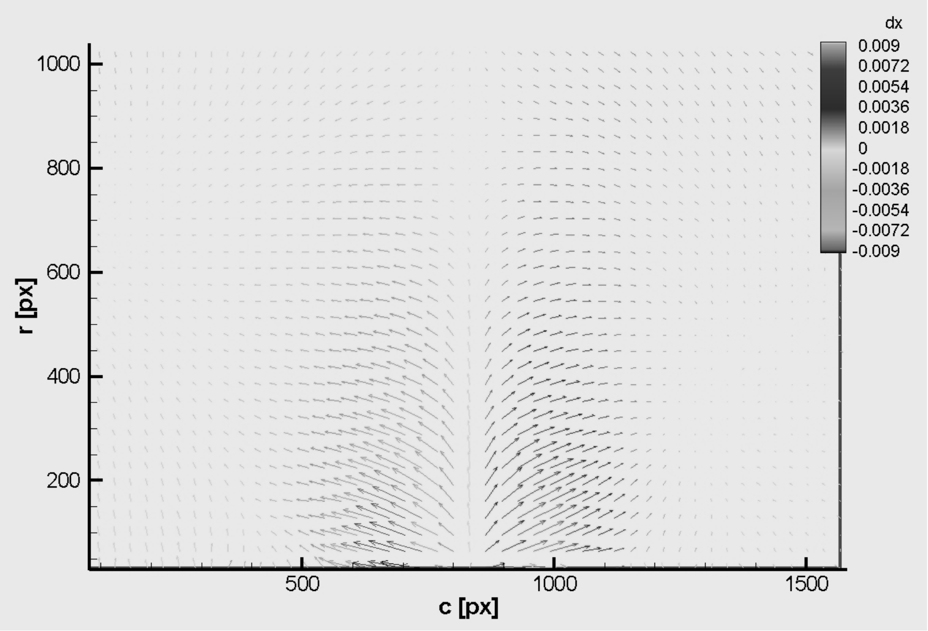

Fig. 4. Average displacement vector field (3 x 10^{-4} pixel rms) out of 700 independent dot patterns with an Astrium nozzle flow (from bottom) in vacuum (8.2 x 10^{-3} mbar) and 2 mg/sec N_2 mass flow.

4. Reconstruction of the density field

For the reconstruction of the three dimensional density fields filtered backprojection was used, which is an inverted Radon-transformation. The Radon-transformation map is an integral over an arbitrary function (f(x,y)) to a point in the Radon space (p).

$$p(l,\Theta) = \mathcal{R}(f)(l,\theta) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)\delta(x\cos\Theta + y\sin\Theta - l)\,\mathrm{d}x\,\mathrm{d}y$$

The BOS – measurement acts as a Radon-transformation, here the integrand is the gradient of the density. The Fourier-Slice-Theorem gives the possibility to go back from the Radon space via the Fourier space in the position space. The filtered backprojection algorithm uses this theorem for reconstructing the density; additionally a filter is used in the Fourier space. An overview is given in Fig. 5 (left).

For reconstruction of the three dimensional density fields some parameters have to be determined. Additional to the scale of the background and the object-plane, information about the refractive index of the environment (n_0) and the Gladstone-Dale-constant (K) depending on the wavelength of the light (λ) and the properties of the fluid is needed.

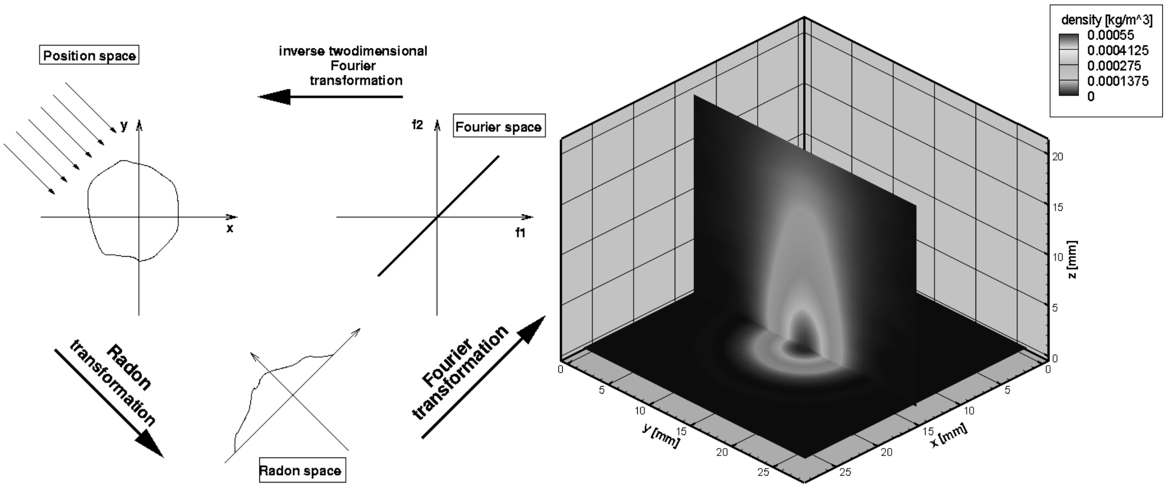

Fig. 5. Overview of the filtered backprojection algorithm (left) and Tomographic reconstruction of the 3D density field of the Astrium micro thrusters nozzle for the case with 2 mg/sec mass flow with a resolution for the gradient of refractive index of dn/dx = 1*10 $^{-7}$ 1/mm (right).

In Fig. 5 (right) slices from the reconstructed density results in the *x*-*y*- and *y*-*z* layer are shown. Assuming a rotational symmetry, 360 projections of the same field of displacement were used.

5. Conclusion

An advanced BOS measurement system for the detection of very low density- or refractive index gradients have been developed and demonstrated for the application to micro thruster plumes of cold gas in a vacuum tank at ESTEC-EPL. A procedure for the tomographic reconstruction using filtered backprojection of the related 3D density field and its applicability has been shown for a very sensitive case of the cold gas plume in vacuum. The results gaining refractive index gradients of dn/dx ~ 1*10 $^{-7}$1/mm with the presented BOS system are very promising.

References

1. H. Richard, M. Raffel. *Principle and applications of the background oriented schlieren (BOS) method.* Measurement Science and Technology. 2001, 12 (9), pp. 1576-1585.
2. A. Schröder, J. Kompenhans, R. Engler, E. Goldhahn. *Current Topics in Experimental Transonic Aerodynamics.* In: M.L. Riethmuller; VKI; Belgium F. Scarano; TU-Delft; The Netherlands [Hrsg.]: Advanced Measuring Techniques for Supersonic Flows, VKI Lecture Series 2005-01, VKI. 2005, ss. 1 - 23 und 1-8, ISBN 2-930389-57-5.
3. W. Merzkirch. *Flow Visualization.* Academic Press, London. 1987
4. L. Venkatakrishnan, G. Meier. *Density measurements using the Background Oriented Schlieren technique.* Experiments in Fluids. 2004, vol. 37, pp. 237-247.