Experimental Evaluation of the Accuracy of an Enhanced Background Oriented Schlieren Technique

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This paper describes a new method to improve the characteristics of the traditional Background Oriented Schlieren technique whose aim is to produce a quantitative visualization of the density gradient field in an optical transparent medium. The experimental setup of the technique consists basically of a camera, a background pattern and an illumination system. Thanks to the deformation of the background due to the compressible flow (schlieren object), it will be numerically compared with the undistorted background through a cross-correlation algorithm. The background will be generated and experimentally optimised using a Gabor noise function and, then, it will be compared with a standard PIV image evaluating their difference and the performance improvements. Once the background has been chosen, a new enhanced BOS technique will be developed with the objective of removing and minimizing the potential sources of error such as the random error due to the noise in the recorded images or the bias error arising from the process of computing the signal peak location to sub-pixel accuracy also known as peak-locking. Finally, this enhanced technique will be validated through two examples focusing on the study of a rotation of the background and on the measure of the background deformation induced by a lens.

Nomenclature

BOS	=	Background Oriented Schlieren
EBOS	=	Enhanced BOS
FOV	=	Field of View
FFT	=	Fast Fourier Transform
f	=	focal length
K	=	Gladstone-Dale constant
M	=	Image Magnification
n	=	Refractive Index
PIV	=	Particle Image Velocimetry
R(s)	=	Cross-Correlation Function
Z_A	=	Distance from lens to schlieren object
Z_B	=	Distance from lens to background
Z_D	=	Distance from background to schlieren
z_i	=	Distance from lens to image plane
ρ	=	Density
ε	=	Light deflection

I. Introduction

The experimental fluid mechanics is a very important branch of aerodynamics. It can give an impulse to theoretical studies, modelling of flow fields and preparation of numerical simulations.

It is true that computational capability has continued to improve at a substantial place, but it has not come close to reaching a level sufficient to replace the need for experimental data in developmental projects. There are now no credible predictions that computational simulation will replace the need for all data from physical experiments in any significant project.

In relation to the experimental aerodynamics, the flow visualization techniches have an important role and its objective is to get a qualitative or quantitative information relating to some property of the fluid dynamic field. In contrast to other measurement techniques such as the Pitot tube which can only measure one physical magnitude at one point, these techniques obtain information about a specific region of the fluid field. Furthermore, they are non-intrusive techniques or, in other words, they do not disturb the flow. This characteristic is essential when it is necessary to study a high compressible flow when the presence of a probe may cause an undesirable shock wave.

Among the flow visualization techniques, Density-Based techniques are included which are based on the change of the refractive index brought about by the fluid density. Thanks to this, compressible flows can be made visible by means of certain optical methods that are sensitive to changes in the refractive index in the field under consideration.

Due to the change in the refractive index, the direction of propagation of a light wave transmitted through the flow and the optical phase are modified in relation to the properties of the incident light. Therefore, the objective will be to detect and to measure the changes in the refractive index using optical techniques.

Among the various possibilities, Background Oriented Schlieren (BOS) seems particularly attractive because it requires a simplified setup and shares data processing methods with other well established techniques for measurements in fluids, such as PIV.

The fluid mechanical problem areas to which this optical measuring technique can be applied are compressible flow, convective heat transfer, mixing and mass transfer, combustion and flows with density stratification.

II. Background Oriented Schlieren

A. Description of the Technique

The Background Oriented Schlieren, abbreviated as BOS, is an optical density visualization technique which belongs to the same family as Schlieren photography, shadowgraphy or interferometry, among others. It is a relatively new technique whose popularity has grown in recent years.

The main advantage of BOS is that it can be used to measure the density gradient quantitatively. Furthermore, this technique is much simpler than the others because of its easy setup and the use of fewer elements. However, in contrast to the other techniques, BOS uses correlation techniques on a background dot pattern to quantitatively characterize compressible and thermal flows with good spatial and temporal resolution.

Typically, its experimental set up consists of a background pattern, a lens, a camera and a light source as represented in the figure 1[8].

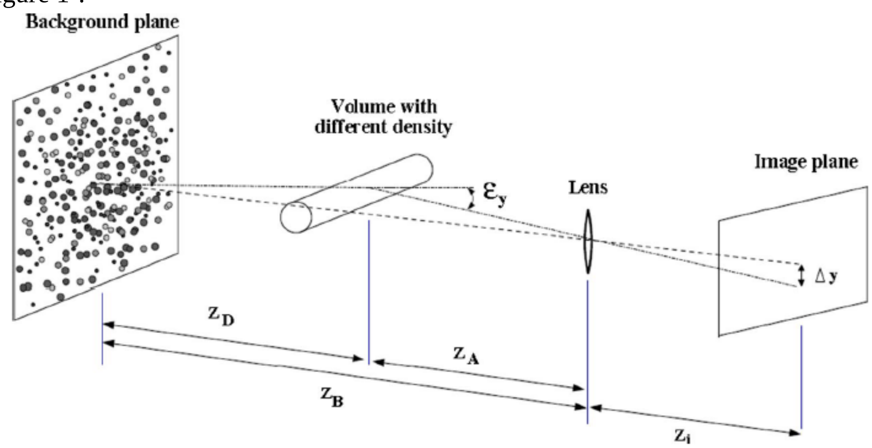

Figure 1. *BOS imaging configuration*

Assuming paraxial recording and small deflection angles, it is possible to compute the image displacement Δy[3]:

$$\varepsilon_y = \text{atan}\left(\frac{\Delta y}{MZ_D}\right) \approx \frac{\Delta y}{MZ_D} \tag{1}$$

Hence:

$$\Delta y = MZ_D\varepsilon_y \tag{2}$$

Where Z_D is the distance between the dot pattern and the volume with density gradient also known as schlieren object, and M is the magnification factor which is defined as:

$$M = \frac{z_i}{Z_B} \tag{3}$$

With the equation (1), the deflection angle can be written as a function of the first derivative of the refractive index:

$$\Delta y = MZ_D\frac{L}{n_0}\frac{\partial n}{\partial y} \tag{4}$$

Where n_0 is the refractive index of the undisturbed medium and L is the thickness of the Schlieren object.

By comparing the disturbed image with the undisturbed one, it is possible to get the displacement Δy using a cross-correlation algorithm.

At the same time, the refractive index is related to the density through the Gladstone-Dale[3] equation and it can be as a thermal property:

$$n - 1 = K\rho \tag{5}$$

Where K is the Gladstone-Dale constant which has the dimension of the inverse of the density and depends on certain characteristics of the gas as well as on the frequency or wavelength of the light used. Moreover, the Gladstone-Dale relation implicitly contains pressure and temperature that can be put in evidence by knowing the equation of state ρ= ρ (T, p).

Finally, the equation (4) can be written as a function of the fluid density thanks to the Gladstone-Dale constant:

$$\frac{\partial \rho}{\partial y} = \frac{1}{MZ_D}\frac{n_0}{LK}\Delta y \tag{6}$$

Therefore, with the value of the displacement measured by cross-correlation methods, it is possible to obtain the fluid density.

In summary, the BOS technique can be divided in three steps:

- Acquisition of an image of the background pattern in the absence of the flow. This image will be the reference.
- Acquisition of an image of the background pattern with the presence of the schlieren object or the compressible flow. In this situation, the pattern will be deformed because of the presence of a refractive index gradient.
- Lastly, the two images will be compared through a cross-correlation algorithm whose function will be to evaluate the virtual displacement of the background in the two directions of de axes.

B. Sensitive and Accuracy

To obtain an appropriate accuracy and sensitivity of this technique is very important that all the experimental components are perfectly aligned and the background pattern must be positioned perpendicular to the z axis.

The correct position of the background pattern is that all its area is in focus. However, there are areas of the background which are closer to the sensor than the others and, therefore, as the depth of field is limited, some areas will not be in focus.

The engineering Erik Goldhan and Jörg Seume[17] have estimated the sensitivity of the Background Oriented Schlieren system which can be defined as:

$$\tan\varepsilon = \frac{\left(1 + \frac{1}{Z_A}\right)\cdot\tan\alpha}{\frac{1}{Z_A} - \tan^2\alpha} \tag{7}$$

Where the typical setup and the definitions of the parameters used in the previous equation are shown in figure 2. It is also shown the minimum value of the derivative dn/dx integrated through the line of sight for three different positions of the schlieren object with respect to the camera and the background.

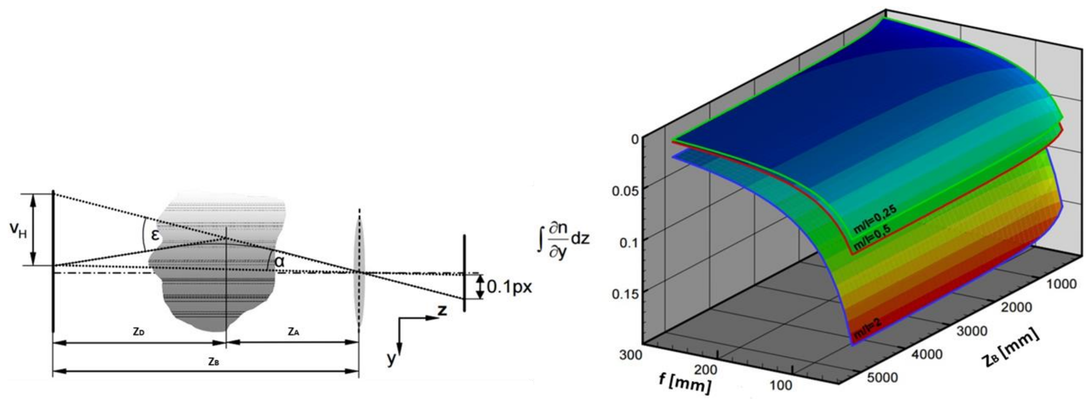

Figure 2. *Sensivity for three different positions of the density object between the camera and the background[17]*

As can be seen, a high sensitivity is obtained with a small distance between the camera and the schlieren object and a great distance between the camera and the background.

C. Cross Correlation Algorithm and its inherent errors

For the quantitative evaluation of the light ray deflection, a technique similar to the Particle Image Velocimetry (PIV) will be used.

Particle Image Velocimetry is a technique of fluid flow measurement and provides instantaneous velocity fields over global domains. It records the position over time of small tracer particles introduced into the flow to extract the local fluid velocity. Thus, PIV represents a quantitative extension of the qualitative flow visualization techniques. The basic requirements for a PIV system are an optically transparent test-section, an illumination light source, a recording medium and a computer for image processing[12].

Cross-correlation methods can be used to measure the separation of pairs of particle images between successive frames. The algorithm takes two areas (interrogation areas) 1 and 2 pertaining to the position of the two images and, statistically, it is possible to compute the pixel displacement measuring the quantity of 1 which must be moved to be as similar as possible to the image 2.

The cross-correlation function R(s) of the intensity patterns $I_1(x)$ and $I_2(x)$ of interrogation spots 1 and 2 is:

$$R(s) = \int_{spot} I_1(x) I_2(x+s)\,dx \tag{8}$$

And using the FFT, it is shown that:

$$R(s) = F^{-1}\{F\{I_1(x)\}F * \{I_2(x)\}\} \tag{9}$$

Where * is the convolution operator.

The correlation produces a signal peak identifying the common particle displacement. Then, an accurate measure of the displacement is achieve with sub-pixel interpolation.

This algorithm has been used with the software *Dantec Dynamic Studio*.

Once the cross-correlation and the peak detection have been done, it is necessary to validate it and to remove the spurious vectors.

To do this, the peak-height validation method has been used during the analysis and it removes all the measurements that do not have an adequate signal to noise ratio. Given the two highest peaks belonging to an interrogation area, φ_{max} and $\varphi_{max\ 2}$, the peak-height validation criterion establishes that the valid measurement is $\varphi_{max}/\ \varphi_{max\ 2} > k$. Where k is equal to 1.2[13].

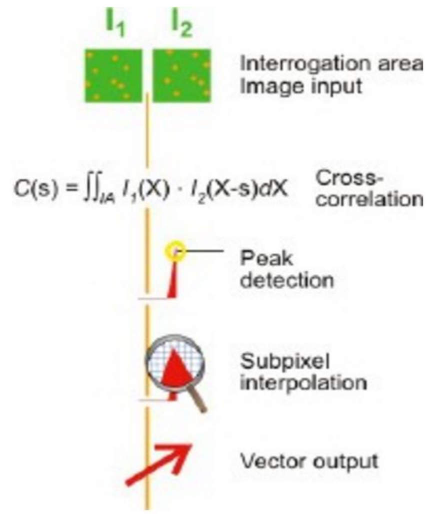

Figure 3. *Cross -Correlation of two interrogation areas*

Peak validation can help to identify invalid vectors, but is unable to produce an estimate of what the correct vector might be. Consequently the invalidated vector will simply be substituted by zero, which in many cases can be quite far from the truth. To resolve this, it is necessary to use the Local Neighbourhood Validation where the individual vectors are compared to the local vectors in the neighbourhood vector area. If a spurious vector is detected, it is removed and replaced by a vector which is calculated by local interpolation of the vectors present in the area.

On the other hand, one of the main objectives of this paper is to improve the accuracy of the Background Oriented Schlieren creating a new enhanced BOS, so the possible source of errors due to the cross correlation technique must be minimized. These sources of errors can be:

- Random errors due to noise in the recorded images.
- Bias error arising from the process of computing the signal peak location to sub-pixel accuracy known as peak-locking.
- Gradient error resulting from rotation and deformation of the flow within an interrogation spot leading to loss of correlation.
- Acceleration error caused by approximating the local Eulerian velocity from the Lagrangian motion of tracer particles.

Some of these errors are inherent to the nature of the correlation and they cannot be eliminated, but their minimization will be possible.

III. Experimental Setup

The experimental setup of the BOS is composed of a traverse system, a CCD camera, an illumination system and a background pattern. Figure 4 shows the representation of the set up in the laboratory. There is also a translator with an accuracy of 2µm whose function is to produce different displacements of the background.

One objective of this section is to determine the relative position between the camera and the background pattern in order to obtain the magnification, M, desired. To do this, it is necessary to use the fundamental optic equation:

$$\frac{1}{z_i} + \frac{1}{Z_B} = \frac{1}{f} \quad (10)$$

Where f is the focal length of the lens, Z_B is the distance between the lens and the background pattern and z_i is the image distance as are shown in the figure 1.

In addition, the magnification of the image can be defined as:

$$M = \frac{z_i}{Z_B} \quad (11)$$

Considering that Z_B is the variable of the problem which can be modified, combining the equations (4.1) and (4.2), the magnification can be express as:

$$M = \frac{f}{Z_B - f} \quad (12)$$

Then, taking account that the measurement of the pixel pitch is 6.45µm, it is possible to express the pixel size in the object plane as a function of the magnification which depends on Z_B:

$$pixel\ size = \frac{6.45 \cdot 10^{-6}}{M} \quad (13)$$

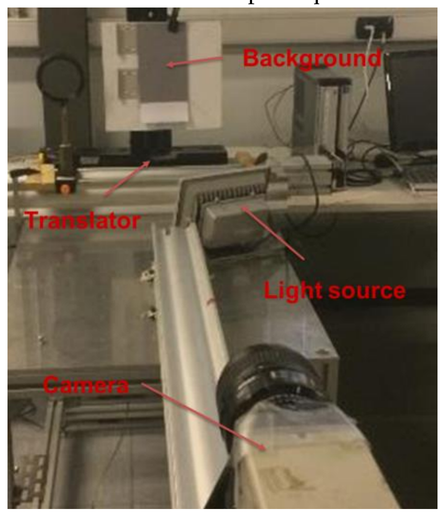

Figure 4. *Experimetal setup*

The field of view (FOV) will be estimated taking account that a CMOS sensor of size 1344X1024 has been used:

$$FOV = \frac{6.45 \cdot 10^{-6} \cdot 1024}{M} \quad (14)$$

This results are presented in the figure 5 as a function of Z_B.

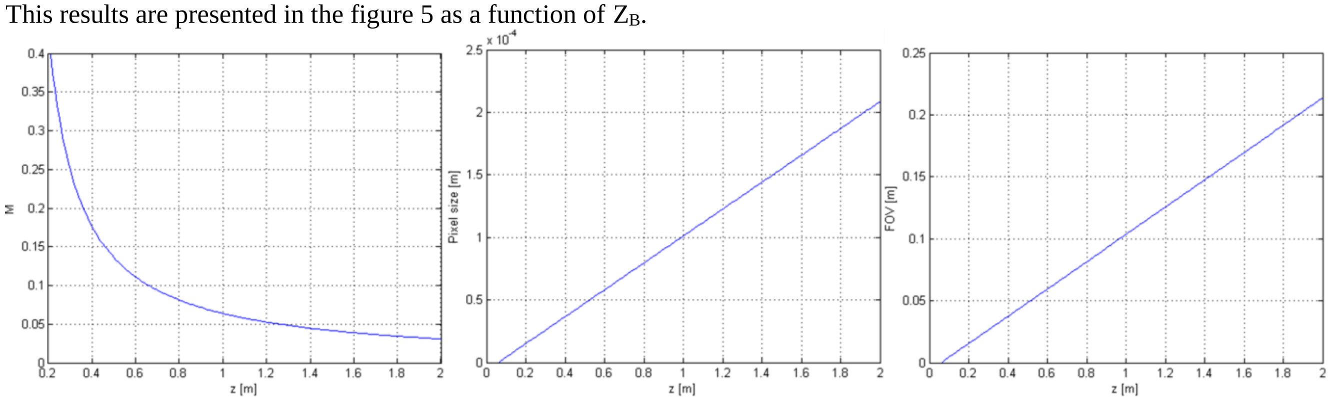

Figure 5. *Magnification, pixel size and field of view as a function of Z_B*

Finally, the characteristic dimensions of the experimental setup have been fixed in order to be used in the different analysis of this paper:

Table 1. *Characteristic dimensions of the experimental setup*

Characteristic Dimensions	
Focal distance	60mm
Lens-Background distance	1,77m
Magnification	0.035
Pixel Size in the object plane	0.184mm
FOV	18.82cm
Diaphragm Aperture	f/8
Exposure time	60000µs

It is important to note that a displacement of 0.1mm of the background corresponds with 0.54pixels.

IV. Selection and Optimization of the Background

One of the objectives of this paper is to design and select an optimal background which minimizes the error of the cross-correlation algorithm studying its behaviour for different criteria. As stated above, the Background Oriented Schlieren technique consists essentially of measuring the deformation of a background pattern. Consequently, its choice is crucial to the proper implementation of the technique.

In theory, any image in grayscale might work, but the choice of an appropriate background will improve the quality and accuracy of the system. For this reason, it is beneficial to have grater details in order to improve the characteristics of the cross-correlation.

With this in mind, several background patterns are used in literature such as PIV images, printed random dots, sandpapers or natural backgrounds.

To check the effect of the background on the results two background patterns have been used: a standard PIV image generated artificially and a new proposal type of background generated through Gabor noise.

The name of the Gabor noise comes from the Gabor convolution and it was created by A. Lagage, S. Lefebvre, G. Drettakis and P. Dutré[14]. The advantage of using this background, as opposed to the others, is that the frequency, which regulates the distribution of the colour, can be controlled very accurately.

Mathematically, the Gabor noise N is defined as a random pulse process (ω_i)with the Gabor kernel g as a pulse:

$$N(x,y) = \sum_{i=1}^{n} \omega_i g(x - x_i, y - y_i) \tag{15}$$

Where n is the number of pulses.

The Gabor kernel is defined as a multiplication of a Gaussian envelope and a harmonic function:

$$g(x,y) = K e^{-\pi a^2 (x^2+y^2)} \cos\left[2\pi F_0\left(x cos(\omega_0) + y sin((\omega_0))\right)\right] \tag{16}$$

Where K and a are the magnitude and width of the Gaussian envelope and (F_0, ω_0) is the frequency of the harmonic in polar coordinates.

Two main parameters are presented with the goal of being optimised. F_0 controls the thickness of the structure and a controls the amount of frequency presented.

Finally, the image of the background can be generated with a program in C++ developed by Lagae[14].

Several backgrounds with different parameters have been experimentally tested and optimised with a preliminary evidence that the best Gabor noise background corresponds with F_0=0.2 and a=0.05.

Once the background has been chosen, it is necessary to compare it with a standard background in order to validate its behaviour and characteristics and to see the improvements with regard to a PIV image which are most commonly used as backgrounds for the BOS.

The synthetic images used in the present work were generated using the EUROPIV Synthetic Image Generator which is described in B. Lecordier, J. Westerweel. The EUROPIV Synthetic Image Generator (S.I.G.). Proceedings of the EUROPIV 2 Workshop on Particle Image Velocimetry. M. Stanislas, J. Westerweel. Springer Verlag, 2004[18].

The PIV synthetic Image Generator (SIG) allows the generation of identical synthetic PIV images in different teams and to simplify the performance evaluation of PIV processing algorithms. The SIG program includes realistic physical models with numerous adjustable parameters. The program is written in ANSI C and can be compiled with any ANSI C compiler.

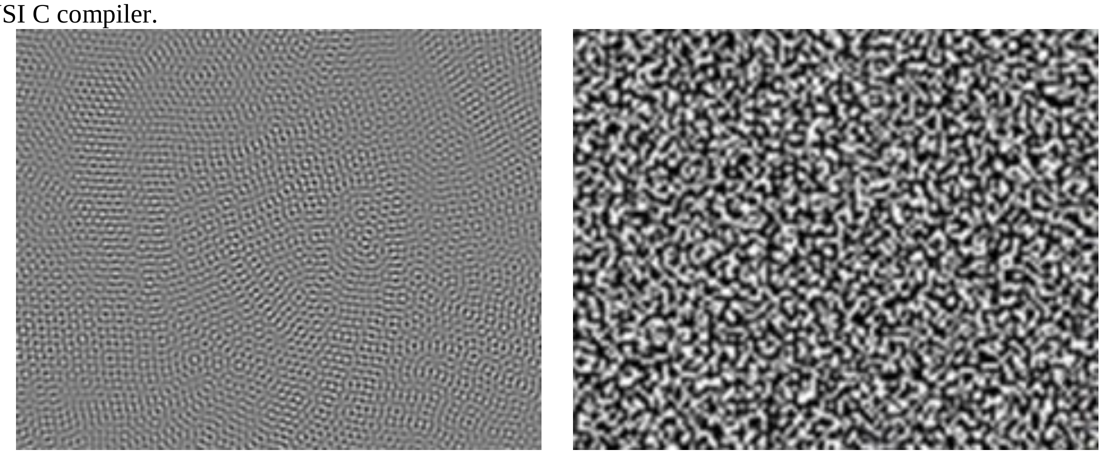

Figure 6. *Enlarged Gabor noise background (left) and a standard PIV background (right)*

V. Enhanced BOS Technique

The main objective of this paper is to develop a new enhance Background Oriented Schlieren Technique which minimizes the errors of the cross-correlation algorithm improving considerably the accuracy and the results of the technique.

As previoulsly explained, the traditional Background Oriented Schlieren Technique consists basically of the cross-correlation of two images in order to obtain the quantitatively deformation of the image due to the insertion of the Schlieren object. Thanks to the displacement measured, the density field of the fluid may be computed.

This new enhanced technique consists of having N images slightly different without the Schlieren object and one image with it, where N will be a great number around 100. Ideally, it would be interesting for the number yo be as high as possible but, unfortunately, it would dramatically increase acquisition and computational time. Each image without the Schlieren object will be compared with the same deformed image due to the fact that the Schlieren object obtaining N cross-correlation maps. The result of this new enhanced BOS (EBOS) technique will be the mean of all these cross-correlations maps where a reduction of the errors and an improvement of the accuracy will be observed.

The N images, which correspond with the number of displacements of the translator, will be randomly taken but with two important considerations:

- The first and last image will always be the reference image or, in other words, the translation always starts and finishes in the same position.
- It is of extreme importance that the mean of the N images is always the reference image in order to make a reliable comparison with the traditional Background Oriented Schlieren Technique. This is equivalent to saying that the arithmetic mean of all the displacements is equal to zero.

All the N images will be different due to a very minimal displacement of the translator of range of less than a pixel which is approximately equivalent to 0.184mm in the object plane.

The displacements of the translator have been carried out through a square grid whose centre corresponds to the reference following a uniform distribution. After each displacement, each photo is taken. The figure 7 shows an example with a number N equal to 50 in a square of side of ±0.3mm.

As has already explained, the first photo will be taken in the origin (0, 0), also called reference position. After that, the translator will randomly move to all positions and will finish at the origin repeating the first image. It should be made clear that the translator only crosses once each position so only one photo will be taken for each.

Lastly, as can be observed, the mean of all the positions of the figure 7 is equal to zero as previously indicated, therefore the mean of the N images equal to the reference one.

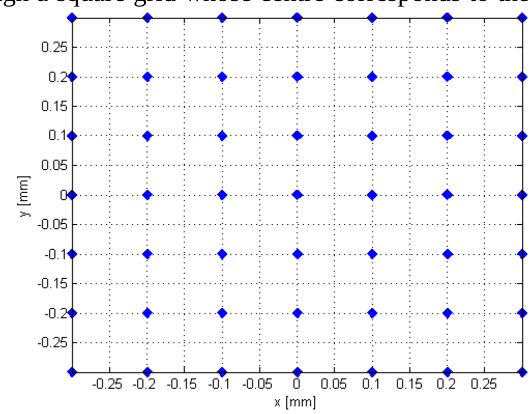

Figure 7. *Square grid of dimension ±0.3mm for 50 displacements*

Once the new enhancement technique has been explained, two experiments will be carried out in order to validate and to observe the improvements of the technique.

The first (A), a rotation of the background will be simulated and error reduction errors will be studied as a function of the number of images taken and of the size of the interrogation areas.

The second (B), consists of study the deformation introduced by a lens which simulating the Schlieren object.

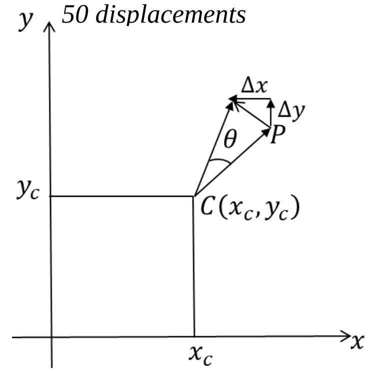

Figure 8. *2D rotation around an arbitrary point*

A. Study of a Rotation of the Background

This experiment consists of the simulating of a small rotation of the background and in evaluating the reduction of possible errors as a function of the number of images taken and the background used.

N images, all of them different due to a small displacement of the background, are taken with the background in the reference position that is the vertical position. After that, the background will be slightly rotated simulating the introduction of the schlieren object and one photo will be taken which will be compared with the N images with the background in reference position.

In order to increase the precision of the mathematical model to obtain a more reliable error, the hypothesis of small angle is not used. In this way, the displacement due to the rotation is equal to:

$$\begin{cases}\Delta x = (x - x_c)(\cos\theta - 1) - (y - y_c)\sin\theta \\ \Delta y = (y - y_c)(\cos\theta - 1) - (x - x_c)\sin\theta\end{cases} \quad (17)$$

Where Δx and Δy are the displacements, θ is the angle rotated and x_c and y_c are the coordinated of the centre of rotation.

It is observed that the displacement (Δx,Δy) of a point P(x,y) due to a rigid rotation around C (x_c,y_c) is a linear function of both (x-x_c) and (y –y_c). Hence, it is possible to obtain the equation of two planes:

$$\begin{cases}\Delta x = A_x x + B_x y + C_x \\ \Delta y = A_y x + B_y y + C_y\end{cases} \quad (18)$$

Where A, B and C are constants which depends on the center of rotation and the angle rotated.

Therefore, it is possible to develop a least square method in order to obtain the value of these constants and, consequently, the center of rotation and the angle rotated as can be seen in the figure 9.

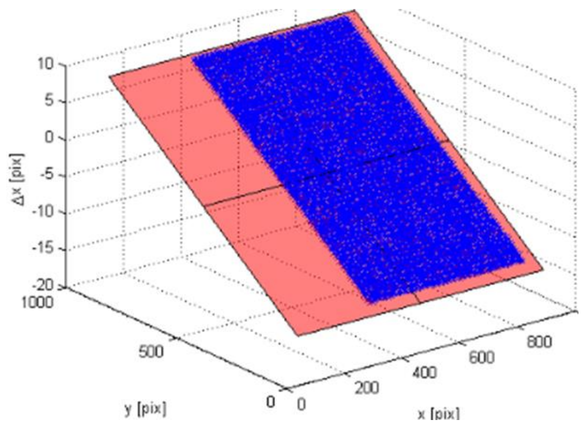

Figure 9. *Least square plane of the horizontal displacement*

Now, let us define an error as the difference between the measured displacement and the plane computed with the least square method:

$$\begin{cases}\|e\| = \sqrt{e_x^2 + e_y^2} \\ e_x = \Delta x^{mis} - \left[(x - x_c)(\cos\theta - 1) - (y - y_c)\sin\theta\right] \\ e_y = \Delta y^{mis} - \left[(y - y_c)(\cos\theta - 1) + (x - x_c)\sin\theta\right]\end{cases} \quad (19)$$

Thanks to the definition of this error, it is possible to compare the different experiments and to see the main advantages of the new EBOS technique.

- Influence of the interrogation areas and the translator movement

Several cases have been studied in order to see the influence of the size of the interrogation areas and the size of the square grid where the translator is moved.

All experiments have been carried out for the noise Gabor background and for three different interrogation areas: 32x32 with an overlap of 75%, 16x16 with an overlap of 75% and 8x8 with an overlap of 50%. Furthermore, three different square grids have been used which correspond to a side of 0.3, 0.15 and 0.1mm.

In order to evaluate the error, its standard deviation has been used. This is a useful criterion because it is a measurement used to quantify the amount of variation or dispersion of a set of data values. The lower the standard deviation, the less the errors will be. This means that a low standard deviation indicates that the desired displacement tends to be close to the mean which is the expected value.

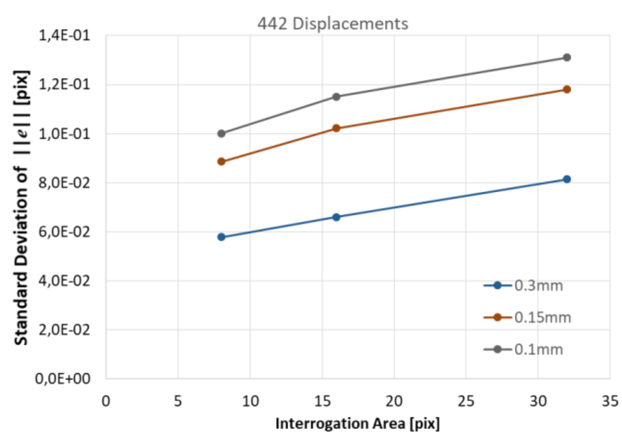

Figure 10. *Standard deviation as a function of the interrogation area*

Figure 10 shows the representation of the standard deviation as a function of the size of the interrogation areas for the three different cases. It is observed that the error always decreases with the reduction of the interrogation areas and is smaller for the case of a square of a side of ±0.3mm.

One of the most important aspects to study is the problem of the peak-locking which can be detected by inspecting the displacement histograms. The peak-locking or pixel-locking is a serious and relevant bias error source introduced with the cross-correlation algorithm and one of the objectives is to reduce it with the enhanced technique. It affects the ability to measure the displacement of a particle with subpixel accuracy from the discrete spatial information provided by the image sensor and it increases the occurrence of measurements close to integer values, deforming the displacement histograms. During the process of determining the displacement to sub-pixel accuracy, the resulting value is always biased towards the nearest integer-valued pixel. Bias error is always zero if the particle is displaced exactly n pixel or n+0.5 pixels, where n is an integer. For displacement n<Δx<n+0.5 pixels, the measured displacement is biased towards n, and for n+0.5< Δx<n+1 pixels, the measured displacement is biased towards n+1.

Figure 11 shows the histogram of the horizontal displacement of the tradiotional and the enhanced BOS techniques. The peak locking error is evident in the traditional technique while in the enhanced one there is a significant reduction. This reduction will be bigger if the size of the interrogation areas is smaller. Therefore, maximum reduction is achieved using interrogation areas of 8x8 pixels.

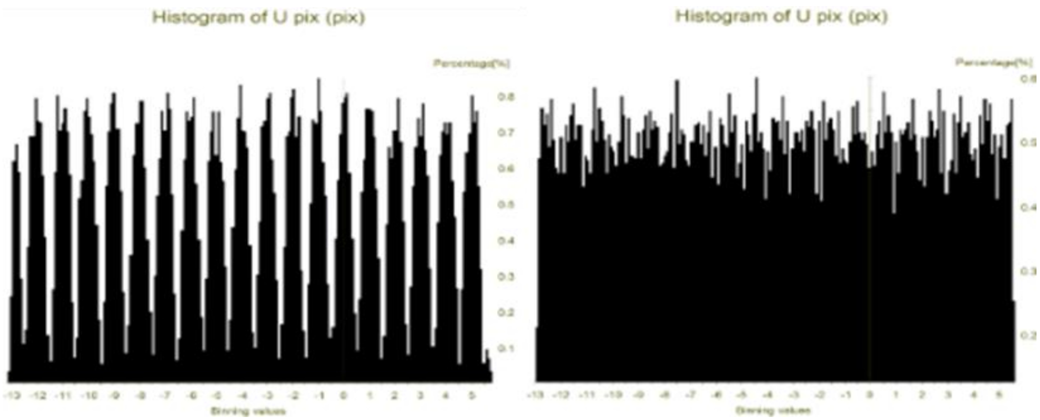

Figure 11. *Horizontal displacement histograms for the traditional (left) and enhanced (right) BOS techniques with 442 images and with an interrogation area of 8x8 with an overlap of 50% for 442 background displacements in a square of side of ±0.03 mm*

➢ <u>Influence of the number of images and of the background used</u>

At this point of the research, it would be useful to see the error evolution in terms of the number of images taken. To do this, the case of the square of ±0.3mm with an interrogation area of 8x8 has been chosen because it presented the minimum error.

The results of this test are shown in the figure 12 where it is possible to observe an error reduction with the number of images, observing that it converges approximately with a number of 100 images.

It is further observed that the background generated with the noise Gabor works better than the PIV one presenting a lower error.

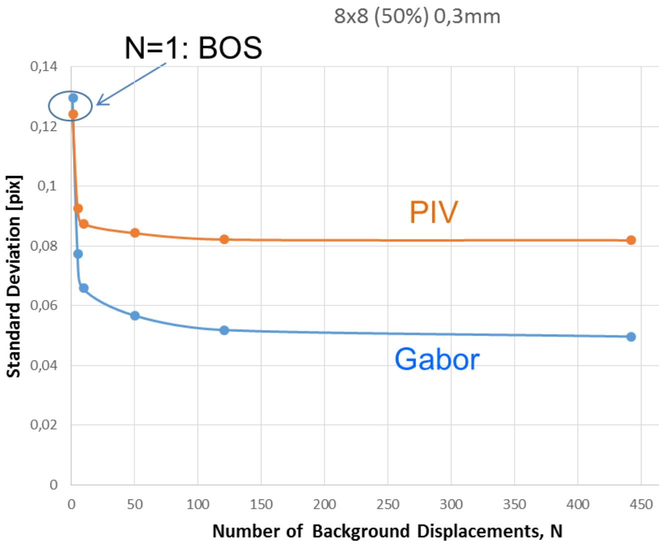

Figure 12. *Standard deviation as a function of the images number*

B. Study of the deformation induced by a lens

A new experiment will be carried out in order to validate the results previously obtained and to demonstrate the improvements of the enhanced BOS technique. The schlieren object will be simulated by a lens and the objective is to measure the deformation induced by the lens comparing the results obtained by the traditional and the enhanced BOS technique.

The procedure is similar to that explained in the previous section. First of all, the deformation will be measured through the traditional BOS. It will then be compared with the enhanced technique where 442 images without the background will be randomly taken around a squared of side of ±0.3mm which was the case with better performances.

Figure 13. *Setup with the lens*

Figure 13 shows the experimental set up with the introduction of the lens of 1200mm focal length. The distance between the lens and the background is equal to 31mm. The distance chosen is the smallest possible in order to avoid an excessive augmentation and displacement of the particles.

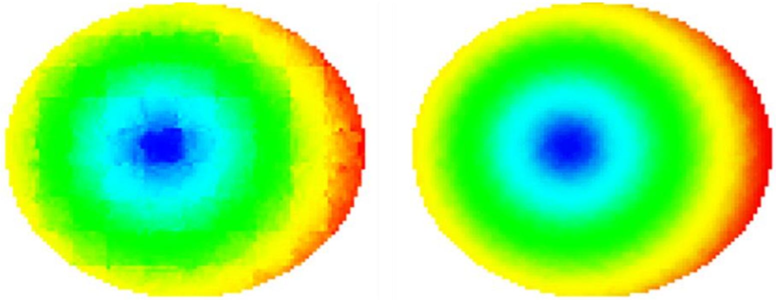

Figure 14. *Displacement generated by the lens in the BOS (left) and EBOS (rght) for an interrogation area of 32x32 pixels*

Similar results have been obtained in comparison to the previous test, improving the accuracy of the technique by reducing the error and the peak locking.

The first notable difference is observed in the representation of the displacement defined as $\sqrt{\Delta x^2 + \Delta y^2}$ where Δx and Δy are the horizontal and vertical displacement, respectively. It is noted that in the enhanced BOS technique the accuracy increases significantly, reducing the noise which is introduced in the traditional technique creating a new cleaner structure. This improvement occurs in all the interrogation areas tested which are: 32x32, 16x16 and 8x8 pixels. An example of this is shown in the figure 14 corresponding with an interrogation area of 32x32.

Now, let us compute the error of the linear regression of the displacements. As before, the error is defined as the difference of the distance between the linear regression and the value measured. Figure 15 shows this displacement and its respective linear regression for BOS and EBOS:

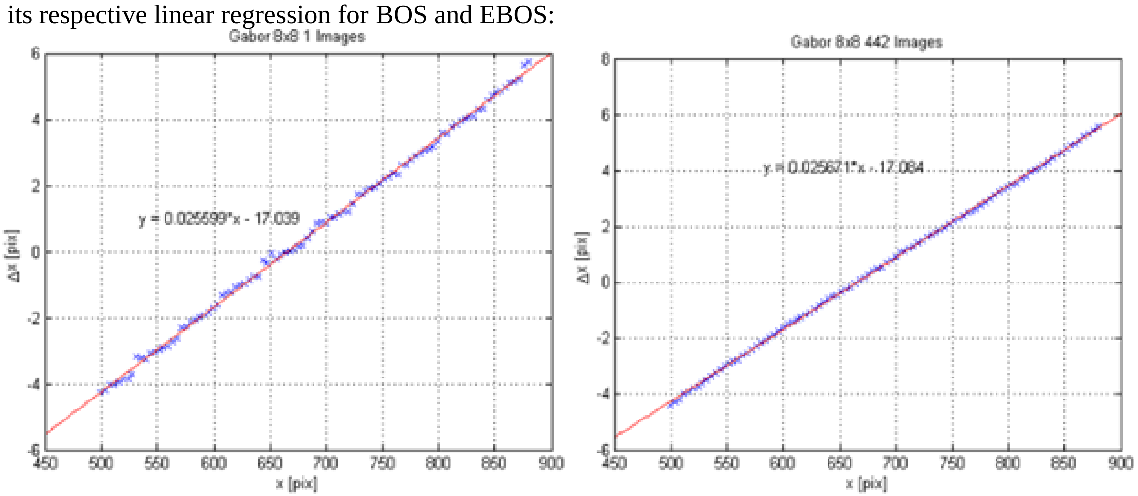

Figure 15. *Linear regression of the displacement for the BOS (right) and EBOS (left)*

Once the error is computed, its standard deviation is calculated in order to obtain a quantitative measurement.

As can be seen in figure 16 the error is always lower in the new EBOS technique with a large increase of the accuracy for small interrogation areas.

It is noted that in traditional BOS, the error always increases when the size of the interrogation areas decreases. However, in enhanced BOS this error is practically constant and less than in the previous technique. While it may appear that the performances could be the same according to the interrogation area, the interrogation area corresponding to 8x8 pixels presents better performances with regards to the peak-locking.

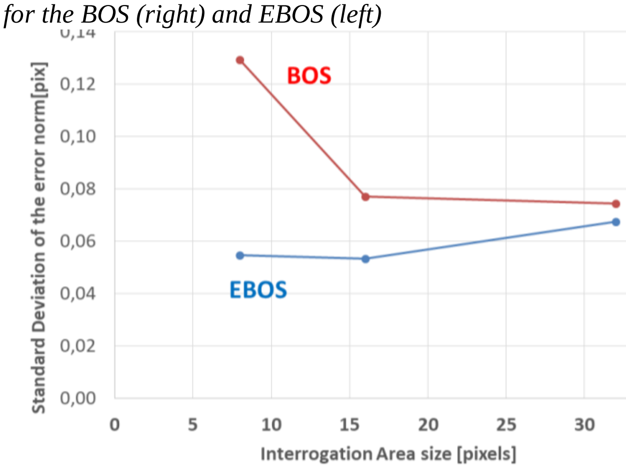

Figure 16. *Standard Deviation as a function of the interrogation areas size*

VI. Conclusions

Background Oriented Schlieren is a modern technique of optical density flow visualization which allows us to measure quantitatively the density gradient. This technique signifies an enormous breakthrough in the experimental fluid dynamic field due to its simple setup and the use of fewer elements with respect to others techniques.

A new enhanced BOS technique has been developed in order to increase its accuracy. First, a new background has been designed through the Gabor noise convolution because of its simplicity and its high control of colour distribution. Its optimization has been carried out via an experimental procedure whose objective was to obtain the appropriate parameters of the Gabor kernel in order to reduce the errors during the acquisition and the cross-correlation algorithm. In order to validate the performances and characteristics of the background chosen, it is necessary to compare it with a standard background to see the improvements with regards to a PIV image, which are the most commonly used in the BOS. As a result, both backgrounds are adequate for the technique, but the one generated with Gabor noise presents better characteristics.

Once the background is chosen, a new idea to improve the accuracy of the BOS is developed and analysed. This new enhanced BOS consists of having slightly different N images without the schlieren object and one image with it, where N is a number of around one hundred. Each image without the schlieren object is compared to the same deformed image due to the Schlieren object obtaining N cross-correlation maps. The result of the enhanced BOS technique is the mean of all these cross-correlations maps where a reduction in errors and an improvement in accuracy is observed. All the N images are different due to a slight displacement in the translator, but it is of vital importance that the mean of all displacements is always equal to zero.

With this new technique, a significantly improvement in the accuracy has been achieved because of error reduction in the cross-correlation algorithm in particular with the peak locking. Furthermore, it has been observed that the accuracy increases rapidly with the number background displacements and it shows considerably better behaviour for small interrogation areas with respect to the traditional BOS.

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