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Executive Summary of the Thesis

Enhanced BOS optimization and experimentation on a hydrogen flame

Laurea Magistrale in Aeronautic Engineering - Ingegneria Aeronautica

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1. Introduction

The Background Oriented Schlieren (BOS) is an optical technique that allows to quantitatively measure density gradients in transparent flows.
The BOS belongs to the Schlieren techniques family, and it is based on the deflection encountered by the light rays as they pass through a medium with non-constant density. The light deflection can be appreciated by the use of a background, where a pattern (usually white dots on a black background) is present. An image of the background distorted by the fluid is compared to an undeformed picture: thanks to the adaptive cross-correlation made by a PIV software, it is possible to measure the deflection of the light rays, and thus, thanks to the Gladston-Dale equation [3], to measure the density gradient field.
The Enhanced BOS (EBOS) *makes use of n different undistorted images of a single grey-scale background pattern* [1], and compares this n images to a single Schlieren acquisition; the n pairs of images are then cross-correlated and averaged, to obtain a single map of displacements.
The aim of this work is to maximise the EBOS accuracy in the measure of density gradients, by optimizing the background used for the analyses.

2. Analysis setup

For this work a monitor-displayed background has been used, in order to create different background with ease and to impose a synthetic displacement to it, as explained in 2.2.
The classical setup is thus composed by a camera and a monitor mounted on the same optical rail for alignment, and a schlieren object between the two.

2.1. Background creation

A Matlab set of functions previously used for the PIV has been modified to define the parameters used for the background creation.
A series of background interrogation areas (bIA) is created, and for each bIA a number of particles is defined. The parameters of main interest for the background creation are the following:

- **particle shape**; three different particle shapes were created, with different light intensity distribution over the surface: the "Black and White" particle defines white pixels inside of the particle radius and black pixels outside. The "Gaussian" shape defines the pixel light intensity as a function (a gaussian) of the distance from the particle center. The "Truncated" is a midway of the two, with white particles in a smaller core and gaussian behaviour outside of it.

- **dimension**; the nominal dimension of the particle, as the actual dimension is influenced also by the particle shape.
- **density**; the number of particles in a bIA, or Ni.
- **margins**; the minimum distance from two different particles, imposed mathematically.

2.2. Error definition

In order to evaluate the quality of a BOS and EBOS measure, synthetic displacement fields have been used.
A synthetic displacement field is a mathematical deformation of the background that simulates the actual deformation made by a schlieren object. After a BOS analysis, it is possible to compare the measured displacement field to the theoretical imposed one, and evaluate the difference between the two.
The analysis error parameter is the mean pixel error e_{tot} as defined in [4].

$$\begin{cases} e_u^{i,j} = (u_{disp}^{i,j} - u_{eff}^{i,j})^2 \\ e_v^{i,j} = (v_{disp}^{i,j} - v_{eff}^{i,j})^2 \\ e^{i,j} = \sqrt{e_u^{i,j} + e_v^{i,j}} \\ e_{tot} = \dfrac{1}{N_x N_y} \displaystyle\sum_{i=1}^{N_x} \sum_{j=1}^{N_y} e^{i,j} \end{cases} \tag{1}$$

For each interrogation area of the cross-correlation (cIA) the measured displacement vector is compared to the theoretical one; the mean of the module of all the differences is the mean pixel error, e_{tot}.
Five different synthetic displacement fields have been used, with different characteristics, such as the presence of discontinuities (from zero to second order), and different order of the displacements (constant, linear, parabolic and sinusoidal displacements have been used).

As a preliminary analysis, the uniformity of the monitor was tested.
The monitor showed some non uniform areas, which were mathematically corrected after the acquisition. Two BOS analyses were made, one before and one after the correction, and the comparison showed that the monitor correction is not necessary for a BOS analysis, as it does not increase the measure accuracy.

3. BOS optimization

After having defined a method to evaluate the accuracy of the measure, and having chosen the background parameters to vary, a series of analysis were made to evaluate the e_{tot} as a function of the background parameters. The synthetic displacement used is the "Diagonal" one, which was considered the most complete, as it presents discontinuities and a non linear displacement field.

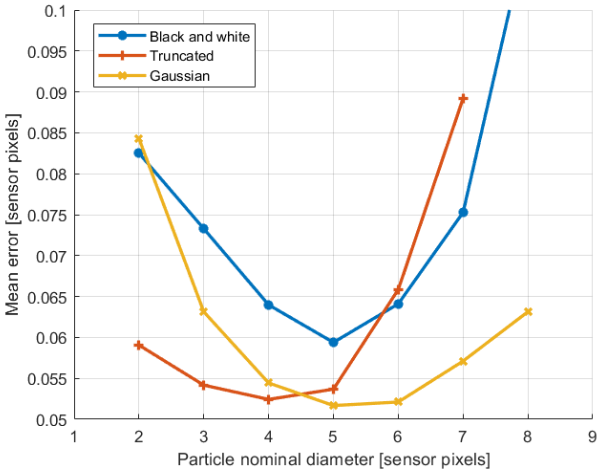

Figure 1: Mean error, e_{tot} for different particle shapes and radii, 1 particle per bIA.

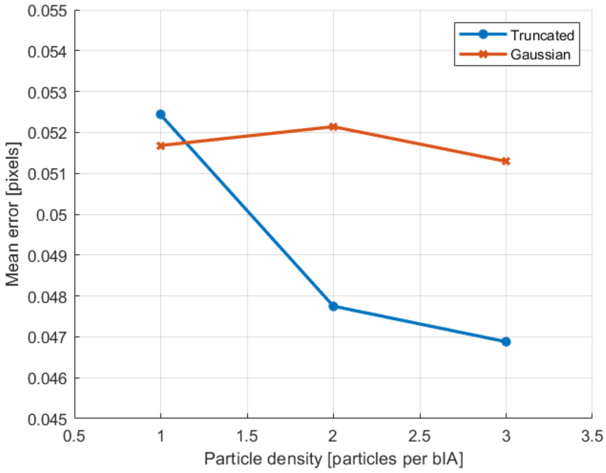

Figure 2: Mean error, e_{tot} for different particle shapes and densities, optimal radius considered for each analysis.

3.1. Influence of particle shape

Figure 1 shows the BOS mean error at the variation of the particle diameter for the three different particle shapes.

For each shape, the behaviour is similar: a parable with the optimal radius at the vertex. This happens because for particles too small the cross-correlation returns a weaker signal, and for particles too big it returns a higher noise. The best results are found when the signal to noise ratio is maximum, condition found at a different diameter for each particle shape.

The "Black and White" particles show an error that is significantly higher than the other two, where Truncated and Gaussian particles give similar errors at their optimal radii. Their behaviour is different, though, when the density is increased (figure 2): Gaussian particles have a more blurred shape, blurring that becomes noise when the particles are smaller and tighter, balancing the improvement brought by the presence of more particles in the same cIA. For this reason, the increase in the particles density doesn't introduce any improvement in the measure. With Truncated particles, instead, the increase in the particle density coincides with a decrease in the mean error.

3.2. Optimal radius and margins

As seen in section 3.1, the optimal radius of a particle decreases if the particle density is increased. The effect of the presence of more particles in the same cIA is similar to the effect of particles too big: the noise increases more than the signal intensity, decreasing the accuracy of the measure.

The optimal diameters found for the Truncated particle, which are 4 pixels at $Ni = 1$, 3 pixels at $Ni = 2$ and 2 pixels at $Ni = 3$, show that the particle area should go from 15% to 22% of the background. This value is of great importance because, given a particle density, it allows to define a priori the optimal diameter, for which the signal to noise ratio is optimal.

A different analysis showed that the introduction of a minimum distance between particles increases the accuracy of the measure. This happens for two reasons: on one side, the overlapping between two particles causes a loss of material to cross-correlate and thus a weaker signal; on the other side, particles more distant are more uniformly spread on the background, and areas without any particle are avoided.

3.3. Software comparison

For the cross-correlation algorithm, the BOS usually used programs made for the PIV. Two different software, Dantec DynamicStudio and OpenPIV were compared, to determine which one is more suitable for a BOS analysis. The same BOS analyses have been made on the two different programs with settings as similar as possible. For this comparison, all the five synthetic displacement fields have been used, in order to compare the software under every aspect. The results showed that the two software have similar overall accuracy, with Dantec being more accurate near zero order discontinuities and OpenPIV being more accurate near higher order ones. In terms of customization, though, being OpenPIV an open source code, it is possible to modify every parameter; whereas Dantec has limited dimensions for the cIA. The possibility to decrease indefinitely the cIA dimensions, increasing the resolution of the measure, was considered a fundamental characteristic of a software and led to choose OpenPIV instead of Dantec.

4. EBOS optimization

In the EBOS, the schlieren image is compared not to a single background image, bu to n variated versions of the same background. The aim of this part of the work was to study the EBOS accuracy depending on the strategy used to create the n backgrounds.

Two strategies have been compared: the *Brownian motion* and the *Rigid Displacements*. The two EBOS techniques have been used to measure the same synthetic displacement field (the Diagonal), with OpenPIV. The results obtained have been compared.

4.1. Brownian motion

The Brownian motion is a local random displacement of the background. A probability density function is defined, and for every particle two values are extracted for both the x and y displacements. This happens independently for each background.

Since the displacements are random, the mean of all the displacements for a particle is not zero, and it is also different from the mean of the other particles.

4.2. Rigid Translations

The Rigid Translations are a global determined shift of the background. A geometric pattern is created, and the n backgrounds are rigid translations of the reference background obtained by following the imposed pattern.

Since the displacements are decided a priori, the mean of all the displacements for each particle is chosen to be zero.

4.3. Results

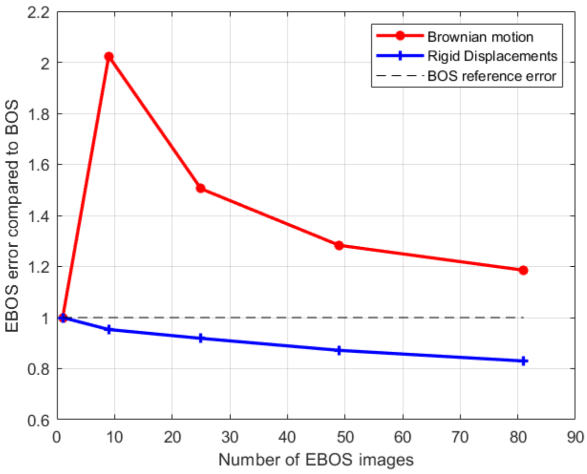

Figure 3: Mean error, e_{tot} of different EBOS methods to the variation of the number of background images.

Figure 3 shows the behaviour of the two different techniques to the number of background images. Both techniques have the same trend, and results improve with the number of backgrounds used, but the Brownian motion EBOS has a higher error than Rigid Displacements and than regular BOS.

This is probably due to the bias error caused by the mean of the displacements being different from zero. It is mitigated by high numbers of images, but not enough to compete with the Rigid Displacements.

A second analysis has been made with smaller cIA dimension (and thus higher resolution), and the results are similar to the ones shown in figure 3. The use of Rigid Displacement EBOS in this case decreases the e_{tot} up to 27%, when in the previous case the e_{tot} decreased up to 17%.

A different analysis compared different Rigid Displacements patterns, and it showed that the improvement introduced by this EBOS is not a function of the actual number of images but to the maximum background displacement (which in previous analysis increased with n). Also, the shape of the pattern resulted not as important as the fact that the mean of the rigid displacements needs to be equal to zero.

5. Experimental study

In order to confirm the improvement introduced by the EBOS, both BOS and EBOS were applied to a hydrogen flame.

The experimental setup was created, by modifying the already existing hydrogen distribution system present at the combustion and optical diagnostic laboratory: a mixture of hydrogen and air exits a Bunsen burner and is ignited by an electrical igniter placed at the tip of the burner. The air and hydrogen flow rates are imposed by a computer as function of the system's thermal power and the mixture equivalence ratio.

The BOS and EBOS backgrounds have been created according to the results obtained in the previous chapters. The background was optimized with small and dense particles with Truncated shape, and a Rigid Displacement EBOS with 81 images have been used.

5.1. Flame stability

In order to avoid flame instability phenomena, and to have the most regular flame as possible, the limits for the flame stability have been studied a priori.

The flame limits for the flashback and for the blow-off has been interpolated from [2] and adapted to the specific case, whereas the limits for turbulence have been calculated from the thermal power and equivalence ratio.

The results presented in figure 4 show a narrow operational area, that is too close to the minimum flow rate of the regulation instruments. For this reason, operational parameters have been increased over the turbulence limit, and since the stability data are only valid for a laminar flame, the mixture parameters have been chosen experimentally.

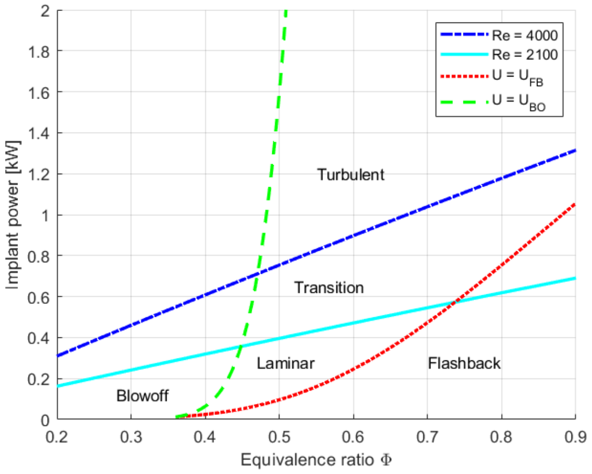

Figure 4: Flashback, blow-off and turbulence limits as function of the plant input parameters.

Three flame conditions have been studied, with increasing thermal power; as the smallest flame was the least turbulent, it has been chosen as test flame. Its parameters are: Thermal power of 1kW and equivalence ratio of $\Phi = 0.45$.

5.2. Flame description

With both BOS and EBOS displacements images it is possible to represent with relatively good resolution the flame and its surroundings.

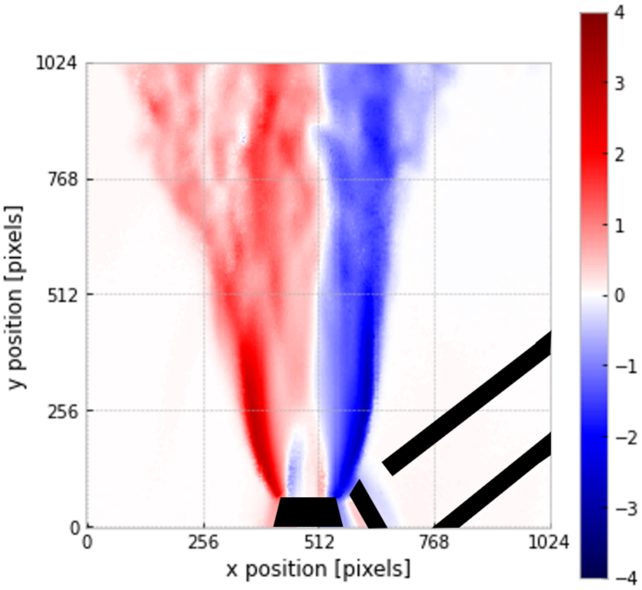

Figure 5: EBOS horizontal displacements, burned and igniter are highlighted in black.

Figure 5 is the integral in the line of sight of the horizontal density gradient of the flame surroundings. Red areas mean a positive temperature gradient, blue areas a negative one. White areas have a constant temperature in the x direction and they can represent the air far from the flame, or the mid-point of the plume, ore the flame front.
The flame is located at the bottom of the image at the center; above the flame a turbulent hot plume is present. The hot burner and igniter heat the surrounding air, that presents a density gradient even if it is far from the flame.

5.3. BOS and EBOS comparison

As no exact displacement field is present to compare the analyses to, the comparison between BOS and EBOS has been made in a different way.
OpenPIV marks the invalid vectors, and substitutes them from the values of the neighbours. For the BOS the marked vectors has been highlighted in brown, and for the EBOS they have been excluded from the average of the n analyses. If less that 5 vectors are valid, the average has not been done and the vector has been highlighted as invalid.

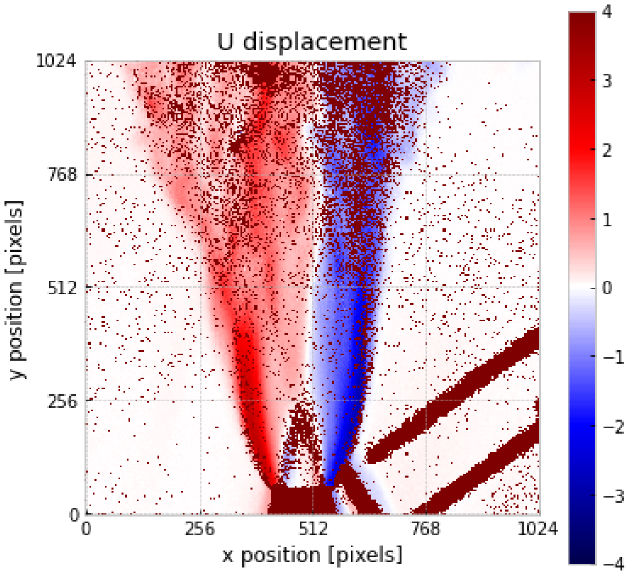

Figure 6: BOS horizontal displacements for the flame. Non valid vectors are highlighted in brown.

As shown in figures 6 and 7, the number of valid vectors for the EBOS is higher than for the BOS, the image is more defined and less grainy. Without considering the vectors invalidated because the background was covered by the burner and

the igniter, the EBOS valid vectors were 99.4% of the total, against the 85.3% of the BOS.
In particular, the EBOS manages to better measure particle displacements even when they are distorted by high density gradients (as it happens at the border of the flame) or by repeated density gradients (as it happens near the flame front and in the plume).

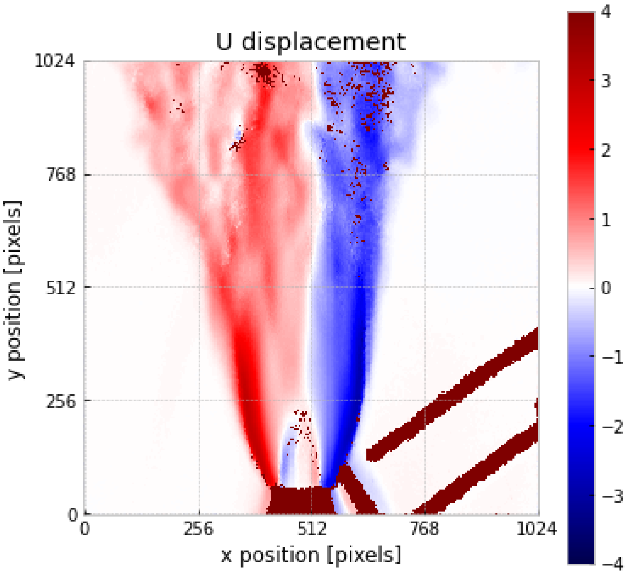

Figure 7: EBOS horizontal displacements for the flame. Non valid vectors are highlighted in brown.

6. Conclusions

After defining a method to evaluate the accuracy of a BOS and EBOS measure, it was possible to optimize some aspects of these two techniques.
For the BOS, the following conclusions has been drawn:

- the shape of a particle influences the accuracy of a measure, the Truncated particle has been highlighted as the better performing.
- The optimal dimension of a particle depends on the particle density; the particle area is suggested to be the $15-22\%$ of the background.
- The overlapping of different particles causes a loss of accuracy in a measure.

The analyses about the EBOS, instead, led to the following conclusions:

- a zero-mean EBOS pattern is necessary to avoid a bias error and a loss in the measure accuracy.
- The Rigid Displacements EBOS generates smaller errors than the BOS, from a small number of images to a large number.
- Greater displacements for the EBOS backgrounds generate more accurate results.

After the optimization, the application to an experimental case showed that the two techniques have the capability of representing complex density gradients with high resolution, with the Rigid Displacement EBOS being a more accurate technique than the BOS.

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References

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