Schlieren Image Velocimetry applied to EHD flows

R. Sosa, E. Arnaud, E. Mémin, G. Artana

Abstract— **In this paper, we address the problem of estimating the motion of fluid flows driven by electrohydrodynamic forces. The fluid motion is visualized through a Schlieren technique is well known in fluid mechanics as it enables pictures of the flow without the use of strange tracers. As the images exhibit in general very low photometric contrasts, classical motion estimation methods based on the brightness consistency assumption (correlation-based approaches, optical flow methods) are rather inefficient. This work aims at proposing a sound energy based estimator dedicated to these particular images. The energy function to be minimized is composed of (a) a data term describing the fact that the observed luminance is linked to the gradient of the fluid density and (b) a specific div curl regularization term. The relevance of our estimator is demonstrated on air flows forced with plasma actuators.**

I. INTRODUCTION

The ability to understand the complexities of fluid flow behavior has large implications in our daily lives and safety as their control and understanding is of the greatest importance in different applications ranging from aero or hydrodynamic studies (air conditioning, aircraft design, etc.) to environmental sciences (wind energy, weather forecasting, climate predictions, flood disasters monitoring, etc.). Flow visualization has been a powerful tool to depict flow features. Efforts to develop high-quality flow visualization techniques date back over a century. The analysis of the recorded images consisted *ab initio* to a qualitative interpretation of the streak lines, leading overall global insight into the flow properties but lacking quantitative details on important parameters such as velocity fields or turbulence intensities. Point measurement probes such as Pitot, hot wire probes or Laser Doppler Velocimetry have typically provided these details. As these probes give information only at the point where they are placed, simultaneous evaluations at different points require to dispose a very large number of probes and the evaluation of unsteady field (most of the flows are unsteady) is almost unachievable.

In an effort to avoid the limitations of these probes, the Particle Image Velocimetry (PIV), a non-intrusive diagnostic technique, has been developed in the last two decades. PIV enables obtaining velocity fields by seeding the flow with particles (e.g. dye, smoke, particles) and observing the motion of these tracers.

An underlying assumption of PIV technique is that the motion of these particles follows the motion of the neighboring fluid. This condition is not always satisfied and requires seeding the flow with small sized tracers leading to an increase of the measurement difficulties.

Some flows may be influenced by the large amount of seeding particles and the seeding may in return alter results. The setting up of the experiment, adjustment of the seeding concentration and other experimental procedures are in general tedious tasks in many large scale facilities. As a consequence this technique is mainly adapted for test in small closed loops wind tunnels. Additional problems appear in the particular case of detailed studies in flows induced by electrohydrodynamic forces. Measurements in regions where a large number of ions are present is a difficult task that can corrupt measurements of hot wire anemometry or results issued from devices that require to seed the flow with tracers. In this last case the electric charging of the tracers can rend the tracer non-neutral and subject to electric forces that promote the “swimming” of the tracer in the fluid. This poses large difficulties especially in EHD flows that induce movements and specially when trying to study the flow induced in quiescent fluid or in regions of an airflow that is in the proximity of a discharge that forces the flow.

Given the various complexities associated to these techniques, it is important to examine strategies that can be used to generate quantitative measurements of unseeded flows. The techniques that provide useful visualization images and, at the same time, yields high-quality quantitative data about the flow are of particular interest. In general Shadowgraph and Schlieren fall into this category [1-2]. These techniques do not require seeding with “non gaseous” tracers since they are based on changes of the index-of-refraction effects produced by changes in mass density fields.

More, if the flowfield is sufficiently turbulent and this turbulence involves refractive-index changes, then turbulent eddies themselves might act as tracers when the flow is viewed using these methods. In such a case the flowfield is selfseeding [3]. An underlying assumption here is that the evolutionary time scale of the eddies is much longer than the time separation of the images pair captured.

In its present embodiment Schlieren Image Velocimetry (SIV) [4] is not useful for laminar flows nor for fully 3Dflows. Otherwise it functions much like standard correlation techniques under conditions where individual particles are not resolved and velocimetry is instead based on estimation of the motion of turbulent structures. The

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integrative nature of Schlieren Technique may be solved when some flow symmetry (v.g. almost planar flows) exist. Eventually when in the spanwise direction are expected differences in phase, gaseous tracers with slight differences of mass density with the surrounding gas (like helium or heated air) may be injected. The tracers incorporated locally can play a similar role to the one of the laser sheet in studies undertaken with 2D particle image velocimetry.

The objective of this work is to analyze the ability of a dense motion estimator to extract velocity fields from Schlieren images of fluid flows induced by EHD forces in a quiescent fluid. To date no satisfying technique exists to perform accurately such velocity measurements. The dense motion estimator we propose here relies on a data model specifically designed for such images. The data model has been elaborated on physical grounds. In addition to this constraint, we have also considered a div-curl smoothing function allowing the preservation of curl blobs.

II. DENSE ESTIMATOR DEDICATED TO SCHLIEREN IMAGES

To construct a relevant dense motion estimator for Schlieren image sequences, it is essential to take into account the physical principle of this fluid visualization method. In particular, when the beam axis of the Schlieren system is disposed in the z direction as observed in figure 1,

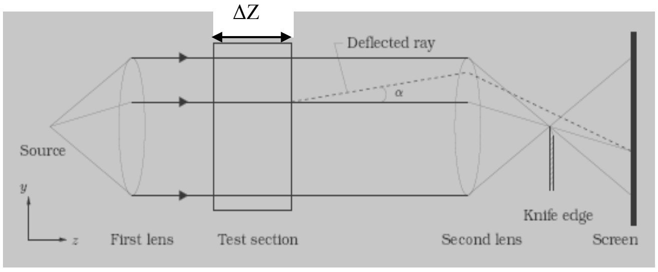

Figure 1: Schematic of Standard Schlieren Assembly

The light pattern I(s) at time t obtained at the screen (or CCD of the camera) is deduced from the mass density of the fluid ρ $I(s) = K\int\left(\frac{\partial\rho}{\partial x} + \frac{\partial\rho}{\partial y}\right)dz$

where the constant K depends on the focal length of the second lens f , C represents the Gladstone Dale constant and a_k denotes the size of the beam cut by the knife. $K = c\frac{f}{a_k}$

In case of an almost 2D flow,

$$I(s) = K\Delta z\left(\frac{\partial\rho}{\partial x} + \frac{\partial\rho}{\partial y}\right)$$

we can easily deduce that

$$\frac{dI}{dt} = K\ \Delta z\left[\frac{\partial}{\partial x}\left(\frac{\partial\rho}{\partial t}\right) + \frac{\partial}{\partial y}\left(\frac{\partial\rho}{\partial t}\right) - \nabla\rho\left(\frac{\partial\vec{v}}{\partial x} + \frac{\partial\vec{v}}{\partial y}\right)\right]$$

by further introducing the continuity equation, we have

$$\frac{\partial\rho}{\partial t} + div(\rho\vec{v}) = 0$$

Under the assumption there is no local favored direction it is postulated that $\frac{\partial\rho}{\partial x} \approx \frac{\partial\rho}{\partial y}$ and it can be obtained the expression of the evolution of the intensity of light on the CCD named data term[4] $\frac{dI}{dt} + \frac{1}{2}I\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right) = 0$

This equation that takes into account the nature of the Schlieren images is the equivalent to the standard brightness constancy assumption used in standard optical flow estimation $\frac{dI}{dt} = 0$. In the differential form the data term is however not useful for estimation of large frame-to-frame displacements and an integrated version of this constraint on the full domain has to be considered. In this integrated version it is convenient also to include a regularization term that establishes an a priori of the fields (v.g. smoothness of the vorticity fields). A more detailed description of the implementation process of the algorithm appear in [4]

III. EXPERIMENTAL RESULTS

In this section, experimental results are presented to highlight the relevance of our estimator. Two kind of EHD flows induced in a quiescent fluid were studied. The first experiment corresponds to a plasma sheet forcing **[5]** meanwhile the second one corresponds to a forcing produced by a conventional dielectric barrier discharge. In both cases the electrodes are disposed along the z direction. The Schlieren system is slightly different from the one of figure 1 as lenses are substituted by parabolic mirrors (diameter 35 mm, focal length 1.5m) that are disposed in a Z type arrangement and two knife edges cut the image both in x and y directions.

The thermal heating of the gas produce mass density alterations high enough to be detected by the Schlieren system in both discharge types. In order to gain in contrast a vertical laminar helium gas jet was also injected in some experiments from small tygon tubes disposed at some centimeters from the discharge.

Figure 2 shows typical Schlieren images of the induced flow by the plasma sheet. In Fig. 2a no He was injected whereas in Fig. 2b the black arrows indicate the positions from which the He was injected.

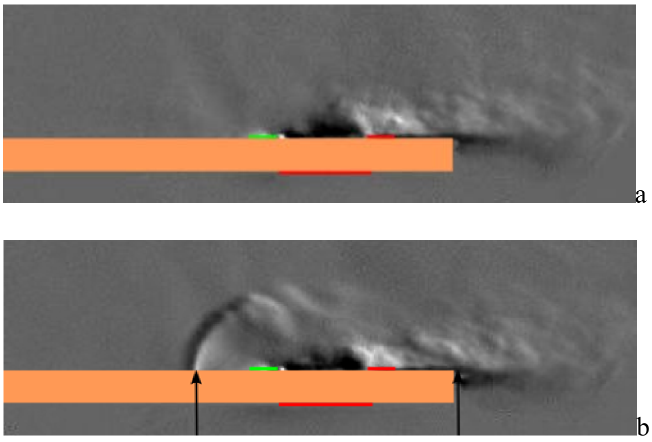

Figure 2: Schlieren images of plasma sheet induced flow
Fig. 2a: no He injection, Fig. 2b : with He injection

Figure 3 shows mean velocity fields obtained by SIV. The average was obtained from 30 instant velocity fields. Figure

3a shows the averaged velocity field obtained without He injection whereas in Fig. 3b He was injected. Although in both cases the SIV computed similar mean flows more details of the induced flow above the inter electrode space were observed when He was injected.

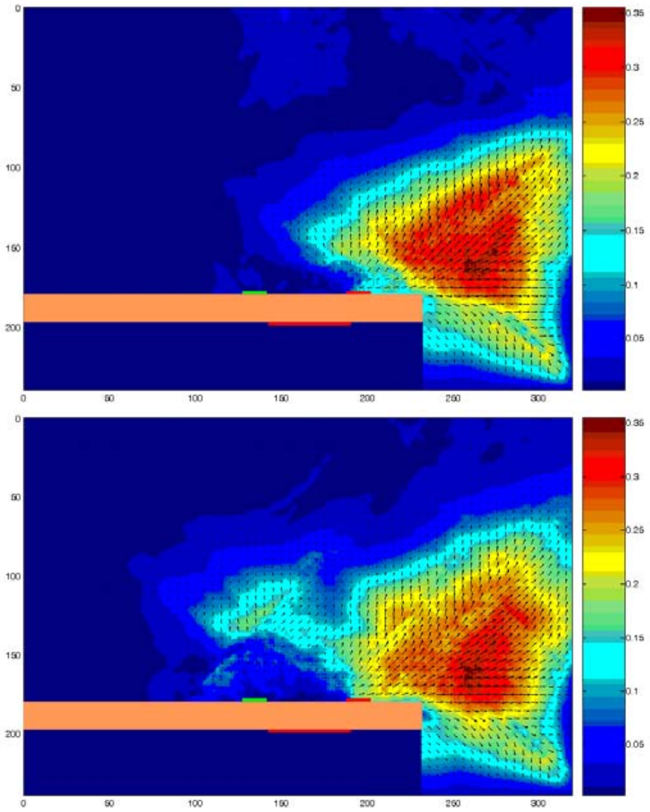

Figure 3: Mean velocity field obtained by SIV
Fig. 3a (upper) : without He injection, Fig. 3b (lower) : with He injection

From the velocity field of Fig. 3b we extracted the horizontal velocity (U_X) profile at 15 mm downstream the upper right electrode. This profile is showed in Figure 4. In order to validate the SIV results with pressure measurements. A pitot tube (internal diameter 0.97 mm) was placed on the dielectric surface at the same position where the velocity profile was obtained. The time-average velocity value measured with the Pitot was 0.4 m/s. When comparing this value to the one btained with SIV we observe consistency of the results but also a tendency to underestimate velocities when using SIV technique.

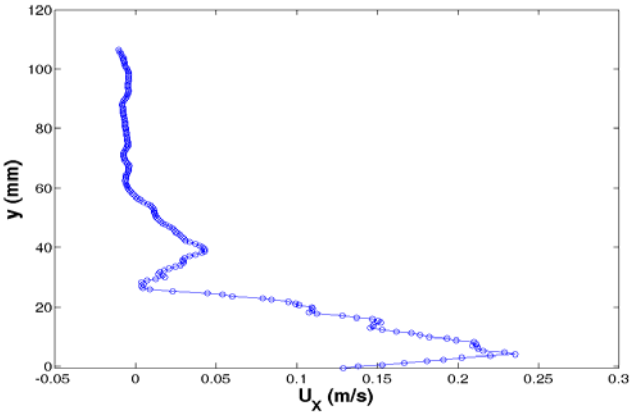

Figure 4. Horizontal velocity (U_X) profile at 15 mm downstream the upper right electrode

We compare our results obtained with our dense motion estimator with the ones issued when applying correlation algorithms (like traditional PIV) to the image processing procedures as recently proposed [3].

Figure 5 presents the averaged velocity field obtained from the same set of Schlieren images of Fig. 3 but evaluated by means of a conventional PIV software **[6].** The algorithm considered an adjustable interrogation area from an initial size (32 x 32) pixels^2 to a final size of (16 x 16) pixels^2. As is showed in Fig. 5 this image process underestimates the velocity field failing and the velocity modulus determined by PIV resulted four times smaller than the velocity measured with the Pitot tube.

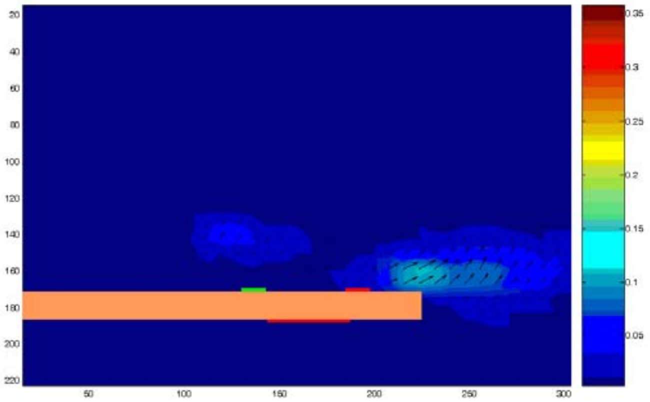

Figure 5: Mean velocity field obtained by PIV with He injection

The results corresponding to second test with a dielectric barrier discharge device are showed in Figures 6 y 7. Figure 6 present a typical Schlieren image of the DBD induced flow. In this image He was injected at positions indicated by the black arrows.

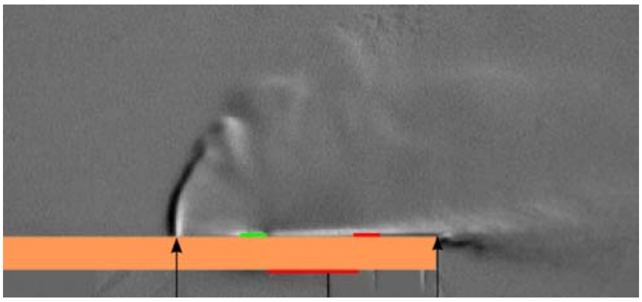

Figure 6: Schlieren images of the DBD induced flow with He injection

Figure 7 shows the mean velocity field of the DBD induced flow obtained by SIV. The average was obtained from 10 instant velocity fields. The flow induced by the DBD also was evaluated with a Pitot placed on the dielectric surface at 15 mm downstream the upper right electrode (45 mm downstream the upper left electrode in which the DBD was developed). The measured velocity value was 2 m/s. The SIV did not allow us to obtain velocities values near the dielectric surface because of the small diffusing character of the DBD induced flow. However for positions downstream close to the He injection SIV could capture velocity values which were consistent with this observed by the Pitot tube. The SIV also reproduce the velocity field close to the He injected from the left position in the non steady laminar regions. There, the density tracers can be identified with a non null velocity and the system can effectively measure the fluctuations on the gradient of the non stationary mass density field.

Again in the cases when analyzing these Schlieren images with PIV processing of (Figure 8) we obtained very poor results and could not capture the velocity field.

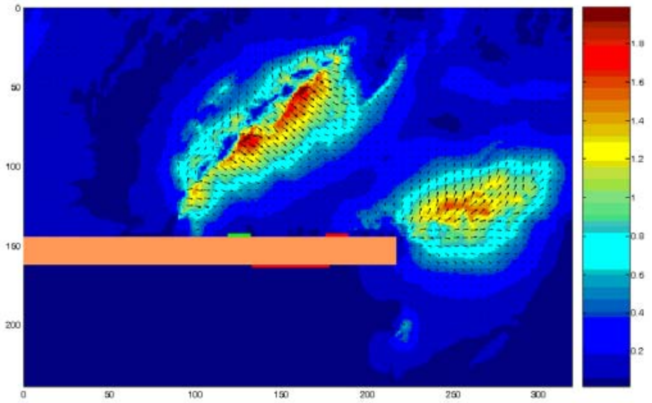

Figure 7: Mean velocity field obtained by SIV with He injection (case of DBD).

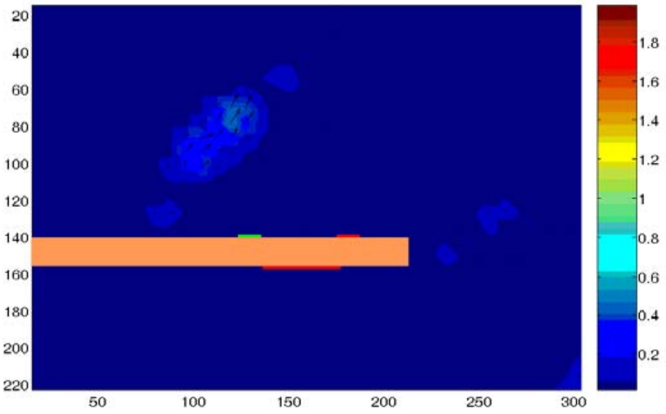

Figure 8: Mean velocity field obtained by PIV with He injection (case of DBD).

IV. CONCLUSIONS

In this paper, we have applied to ehd induced flows a new method for the estimation of dense fluid motion fields dedicated to images obtained with a Schlieren system.

The analysis of the Schlieren images of EHD flows with this technique is of great importance since this system enables the visualization of unseeded flows and in consequence avoids the spurious effect of tracers charging.

The technique enabled a good representation of flows forced with plasma actuators. The technique was tested under one of the most constraining conditions in EHD induced Flow: the motion induced in a quiescent fluid. In this case the technique proved to be very effective to capture the flows produced either with DBD and Plasma Sheet actuations.

By adding small amount of He to the gas, more detailed structures of the flow could be found but in general the small changes in density associated to the slight heating produced by the discharge resulted enough to obtain images of quality.

The very promising results have demonstrated the interest of using such an approach for the Schlieren image analysis instead of classical correlation techniques as PIV that failed to capture field details.

The following planned step is to analyse improvements in ehd flow analysis through improvements in the estimator performance and several perspectives can be investigated such as the study of 3D flows (using for example the Schlieren tomography [7]), and the design of dedicated algorithms to track the fluid structures.

REFERENCES

[1] Settles, G.S., Schlieren and Shadowgraph techniques,Springer , Ny, 2001.

[2] Settles, G.S.: The penn state full-scale schlieren system. In: Int. Symp. on Flow Visualization. (2004)

[3] D Jonassen, G Settles, M D. Tronosky, Schlieren ''PIV'' for turbulent flows, Optics and Lasers in Engineering, 44, 3-4, 190-207, (2006)

[4] E Arnaud, E. Memin, R. Sosa, G. Artana, A Fluid Motion Estimator for Schlieren Imaging Velocimetry, Lecture Notes in Computer Science, Volume 3951 / pp. 198 – 210, (2006)

[5] R. Sosa, E. Arnaud, G. Artana, Study of the Flow Induced by a Sliding Discharge, International Simposium on Electrohydrodonamics (ISEHD), 4-6 december, 2006, Buenos Aires, Argentina.

[6] GPIV references available at http://gpiv.sourceforge.net/

[7] Agrawal, A., Butuk, N., Gollahalli, S., Gri±n, D.: Three-dimensional rainbow schlieren tomography of a temperature field in gas flows. Applied Optics (1998)