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Recent evolutions of imagery in fluid mechanics: From standard tomographic visualization to 3D volumic velocimetry

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Abstract

The recent evolutions of the optical analysis of three-dimensional (3D) flows by means of light scattering and quantitative imagery are presented. In order to remove the intrinsic ambiguity of the well-known tomographic methods (how to obtain 3D information by using a 2D plane illumination?), the efficiency of polychromatic lightings is shown: the basic idea is to code the third dimension by the wavelength.

Different approaches are described: discrete or continuous analysis, sequential or simultaneous recordings, and measurement of two or three velocity components (2C or 3C techniques).

The most recent 3D velocimetry method using a rainbow lighting process (RVV—Rainbow Volumic Velocimetry) is presented. The main qualities and limitations of these different methods are discussed.

Keywords: Flow visualization; PSV; PTV; Rainbow volumic velocimetry; Colour image processing

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1. Introduction

In the field of Fluid Mechanics, the dream of each experimenter is to have at his disposal a universal non-intrusive measurement process able to extract the three velocity components of a three-dimensional (3D) flow, from a large volume, in a great speed range, even with unstationary configurations. In this competition, only the optical measurements allow to give at once the non-intrusive aspect and at the same time a global investigation of the flow field. If we wish to add up the 3D character, the standard "optical methods" (Shadowgraph, Shlieren, Interferometry), based on the exploitation of refraction index variations are not competitive, in spite of their high level of sensitivity: because of their integrating principle, they remain especially adapted to the study of 2D or axisymmetric phenomena. A few other methods are very efficient, like holography (for small volumes) or stereo observations (in the vicinity of a plane).

This paper summarizes another approach: the use of moving light sheets (dynamic tomography) or colour coding in order to obtain more information on the fluid characteristics:

- A first idea is to implement sequential or continuous movements of a standard monochromatic laser sheet. On principle, this approach cannot allow to give the strict simultaneity of the different recorded planes.
- A second step up to the 3D analysis is based on the following idea: the strict simultaneity can be obtained by means of different static and polychromatic light sheets close together.
- Finally, the most recent evolution of the chromatic coding is presented: a rainbow lighting, corresponding to an infinity of different coloured planes gives access to a real 3D velocimetry technique.

2. The standard tomographic approach

The standard laser tomography is born during the 1970s [1–3]. The basic idea which consists of observing the light scattered by low inertia tracers, able to follow accurately the movements of a flow, is not really young since it is attributed to Leonardo da Vinci [4]. In fact, the practical revolution has been the birth of the laser, the only source permitting to generate a very thin light sheet with a high power density, opening the door to the tomographic recordings. The use of very small tracers, in order to respect the inertia condition, became possible because the very small level of scattering light is compensated by the high light intensity of the illumination process. It became popular rapidly because it gives the possibility to investigate non-axisymmetric 3D flows "plane by plane".

The standard illumination device is based on the combination of a focusing function (most often a single lens, sometimes an adjustable telescope) with a spreading function (cylindrical lens or telescope) [5]. We have to note that the usual term "plane sheet" is in fact ill-advised:

Real laser sheets are complex light distributions, whose energy profiles can be calculated if the emission mode of the illuminating laser is known. For example, if the laser cavity operates on a TEM_{00} mode, the geometrical dimensions of the sheets (width and thickness) can be deduced from the e^{-2} width of the cavity waist [6]. In addition, tomographic "light planes" are never light planes.

The most classical solution to improve the light scattering level is to increase the power density by reducing the sheet thickness for a given laser power. This choice is very efficient when the tracers are not individualized: smoke visualizations or "cloud seeding" by submicronic droplets. But, if we have to record images of discrete tracers in order to obtain quantitative information on the velocity field (chronophotography), the flow must be strictly 2D. If not, the tracers do not remain a long time in the laser sheet and the recording duration has to be very short. This condition is respected by using pulsed lasers, which is the usual application field of particle image velocimetry (PIV). If the recording time is not very short [particle tracking velocimetry (PTV) or particle streaking velocimetry (PSV)] the tracers can leave the lighting area and the quantitative analysis of the velocity field becomes partially wrong or even inoperative.

These remarks underline the main limitation of the standard tomographic analysis: how to extract 3D information from 2D investigations?

3. Sequential and volumic tomography: A first step to 3D investigations

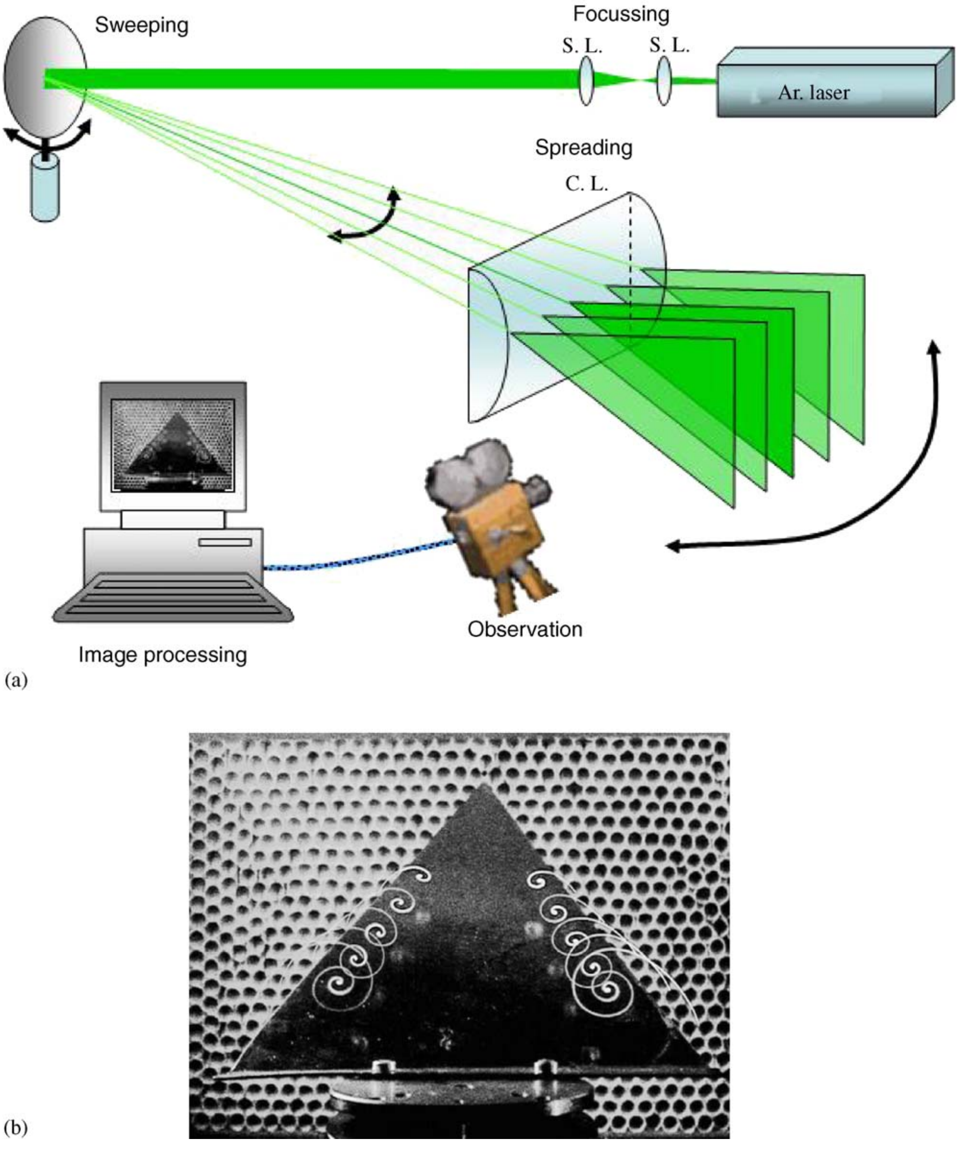
The basic idea of this approach is to use a moving light sheet in order to illuminate different planes of the phenomenon sequentially. Of course, the different tomographic observations are not strictly simultaneous; then, the main fields of application are the steady or slowly variable flows.

Various optical devices can be implemented, based on the combination of the permanent lighting of a spread static sheet with a fast movement generated by an optical scanner: electro-mechanical mirrors if large sweeping angles are wished or acousto-optical deflectors if small and fast shifts are wished. The different motion modes (sweeping function) determine the family of visualization [7]:

- Sequential tomography: the optical scanner being driven by successive step functions, it is possible to record N different plane images of steady or quasi-steady flows (Fig. 1a).
- Volumic tomography: the scanner is driven by an alternative triangular signal (this specific shape gives a quasi-uniform illumination due to the constant shift speed).

The visualization becomes continuous and really 3D in the swept volume. However, the tracer concentration has to be high enough and the global recording yields non-quantitative information on the 3D velocity field (Fig. 1b).

Of course, these two techniques impose an accurate determination of the depth of field of the recording optical system.



(a)

(b)

Fig. 1. Movable laser sheet: optical device (a) and sequential (b) 3D flow visualizations around a delta wing (C.L. Cylindrical Lens-S.L. Spherical Lens).

4. Another way to 3D tomographic analysis: The simultaneous wavelength coding

In the case of strongly unsteady flows, the use of a single tomographic technique imposes to follow the temporal evolution of a sole cross-section of the phenomenon, thus losing the space information, or to shift the recording plane, thus losing the simultaneity. To solve this problem partially, a possible solution is to use a stereoscopic recording (stereo PIV, for example [8]). However, this type of observation remains close to a 2D recording, giving only the third velocity component near a slice of fluid (3C–2D method).

Another way to a partially 3D analysis consists in using multiple simultaneous laser sheets: to avoid the overlapping of the different recordings, the multiple light sheets can be wavelength coded (a polarizing coding is possible too, but for two sheets only [9]).

The basic multi-wavelength device requires:

- a multi-line laser: CW ion laser, argon (green, blue and violet lines) or preferably argon–krypton (additional red line),
- a dispersing component: prism or grating,
- a spreading component: cylindrical lens (static sheet generator),

Usual optical components allow the adjustment of the focusing, the parallelism and the gap between the different beams.

So, a set of N adjoining plane light sheets of N different colours illuminates the flow. For the recording process, the same number of cameras has to be used (practically N from 2 to 4), each of them focused on one sheet. The chromatic selection is assumed by interference filtering, in order to warrant that each recording system only sees one specific plane of the flow. The strict simultaneity is easy to obtain by means of a common shutter, acting upstream on the multi-line laser beam (Fig. 2). So, this method can give strictly simultaneous information on N different sections, qualitative (single visualization) or quantitative (e.g. N close velocity fields), even for unsteady flows [10]; of course, it presents the same disadvantage as stereo recording since a set of cameras is necessary. But, it also presents a lot of advantages: the gap between each section can be adjusted easily and the investigated volume increased easily too. So, the 3D character of the analysis is obtained by a simple addition of N 2D pictures: discrete reconstruction of 3D phenomena.

Theoretically, if the different laser sheets could be strictly adjacent, the use of the wavelength coding could suppress the paradox "3D phenomena–2D analysis". In fact, this condition is impossible to obtain by using standard spread laser sheets, even with ideal gaussian profiles, because of the bad definition of their boundaries. Indeed, strictly adjacent sheets do not exist: a decreasing of the gap between two sheets induces only a complex polychromatic light overlapping, which can sometimes be used to extract information on the tracers positions between two cross-sections [11]. To avoid this complex overlapping, the usual gaussian sheet profile has to be converted into a rectangular profile. A possible solution is to control the light repartition of the sheet by using fast laser beam sweeps. If a finely focused gaussian beam oscillates with a constant velocity (triangular sweeping), the mean power density of its profile becomes quasi-rectangular [12]. Thus, the use of an X–Y beam deflector allows to generate a

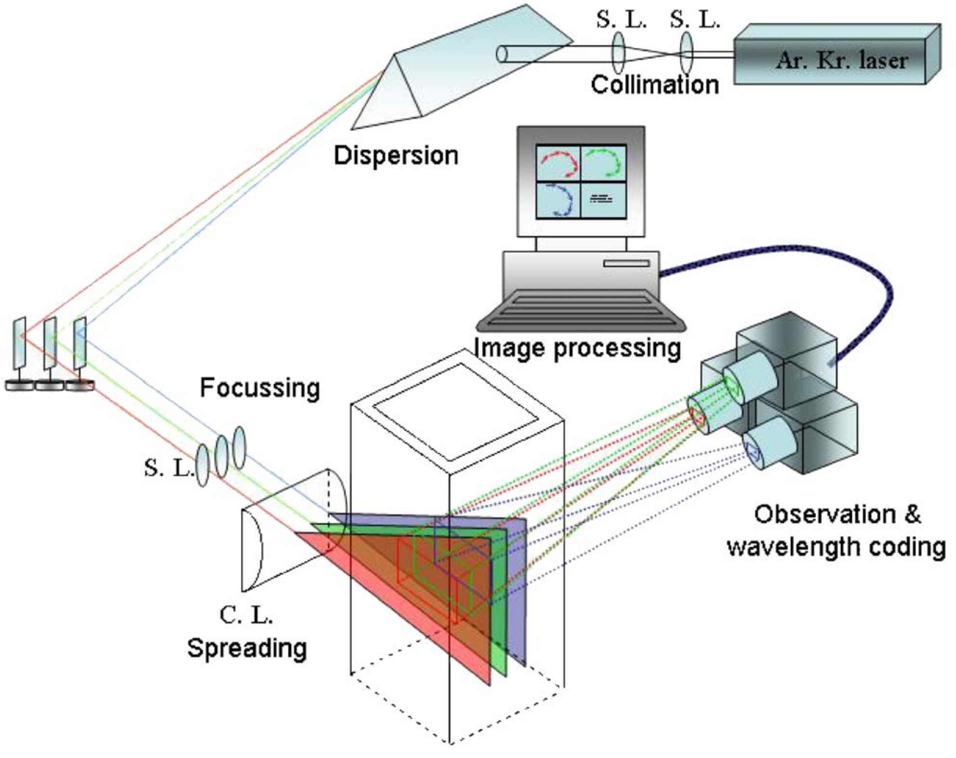


Fig. 2. Wavelength coding tomography. (C.L. Cylindrical Lens-S.L. Spherical Lens).

dynamical light slab instead of a standard sheet. The slab width and thickness become well defined, easily adjustable and its light repartition becomes quasi-homogeneous in the whole volume.

The combination of such a dynamic lighting with a polychromatic illumination allows to obtain multiple homogeneous light slabs of different colours, strictly adjacent or very close, with adjustable gaps.

The typical optical device requires (Fig. 3):

- a multi-line CW laser,
- a dispersing component,
- a double X–Y beam deflector : X—thickness axis, and Y—width axis,
- a set of mirrors and prisms: adjustment of beam parallelism and gaps between light slices.

If three wavelengths are used (most frequent configuration) we can observe on the recorded images three different types of traces (spots in PTV or dashes in PSV):

- Trichromatic if the flow is strictly 3D.

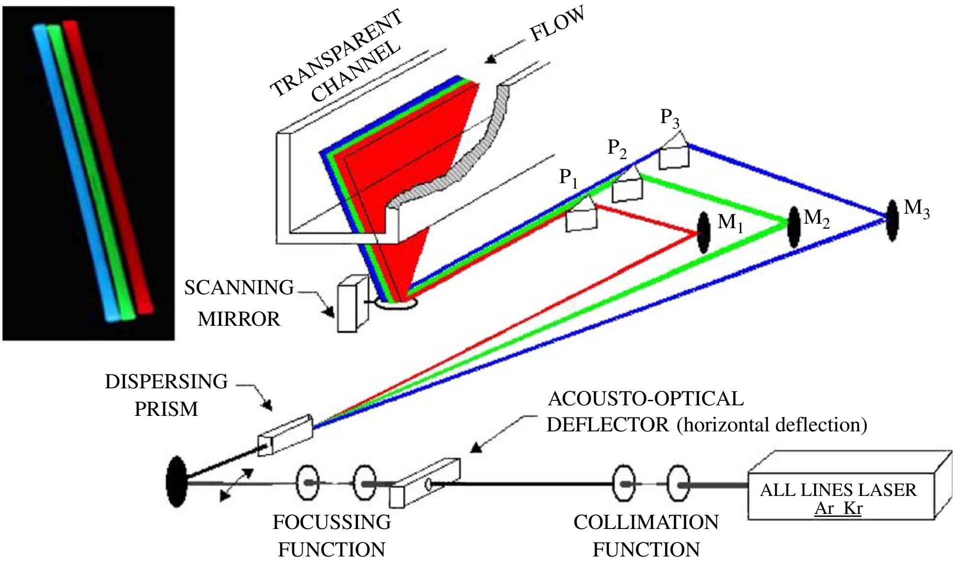


Fig. 3. Polychromatic light slabs—optical device.

- Bichromatic if the flow is weakly 3D and compels the tracers to pass from a coloured volume to another. So, the deviation direction is deduced from the colour change.
- Only monochromatic if the flow is strictly 2D.

Therefore, a measured velocity field can be validated only if the recorded information is monochromatic. On the other hand, the areas where a 3D behaviour appears are easily detected (Fig. 4) [13].

5. Polychromatic continuous spectrum illumination: A way to real 3D investigations

In the previous method, it is impossible, for practical reasons, to increase the number of polychromatic slices strongly. A basic idea to replace an infinity of discrete light planes is to make use of a continuous polychromatic spectrum. If the direction of observation (z) is parallel to the wavelength gradient, the z coordinate of each tracer can be deduced from the colour of the scattered light, the x, y coordinates remaining determined by a usual PTV or PSV image processing. So, the sequential analysis of the successive positions (x, y, z) of each tracer can give the three components of the velocity field in the whole lighted volume. Of course, this approach requires a good knowledge of the relation between each wavelength value in the rainbow spectrum and the corresponding z position in the tested volume. Obviously, we have to avoid strong shifts of the wavelength during the scattering process; thus, a calibration step is necessary to obtain a truly accurate 3D velocimetry: this is the concept of Rainbow Volumic Velocimetry (RVV) [14,15].

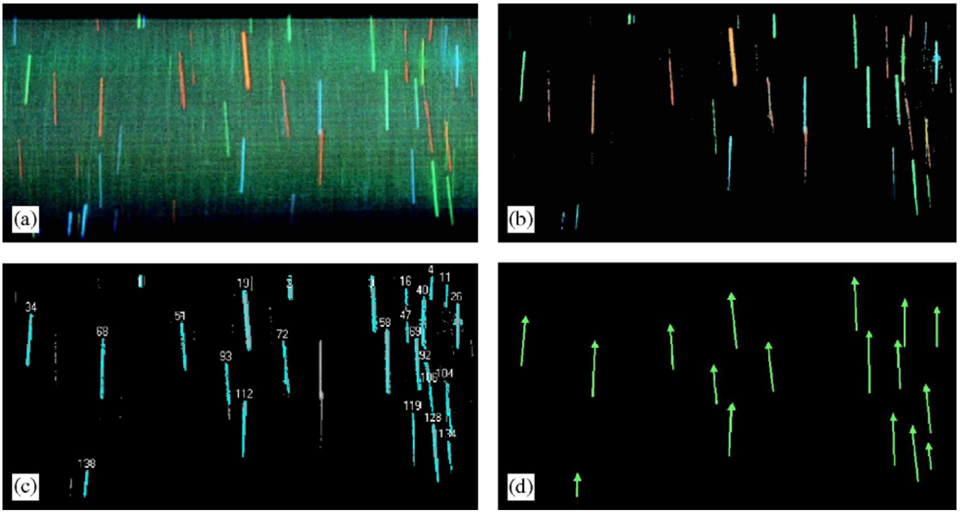


Fig. 4. Polychromatic light slabs: typical observation (a), processed image (b), streaks recognition (c), velocity vector field (d).

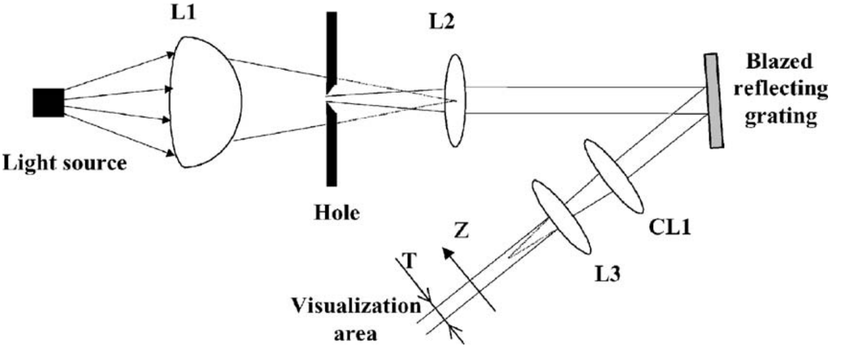


Fig. 5. RVV lighting process.

The basic experimental configuration requires an intense white light source (gas discharge lamp) to be dispersed in order to generate the continuous "rainbow" spectrum: a condenser light L_1 collects and concentrates the white light on a circular pinhole and a collimating lens L_2 gives an almost parallel beam. After this collimating function, a blazed reflective grating ensures the dispersing function. A cylindrical lens CL_1 induces the spreading of the polychromatic beam along one direction in order to generate a parallelepiped of light and a spherical one allows the adjustment of the focusing distance and of the thickness T, the wavelength gradient being parallel to the thickness axis z (Fig. 5).

By using a standard discharge white source, the light power density remains relatively low compared to that obtained with a CW laser in conventional tomography. Typically, with a 100–150 W Xenon lamp, the rainbow volume is limited to $10 \times 10 \times 3\,\text{cm}^3$. An increase of this volume is possible by using powerful gas discharge lamps (500–1000 W), but we have to notice that the thickness is always limited by the depth of field of the optical recording device.

This point is essential because the low level of scattered light due to the small dimensions of the tracers imposes the use of a large aperture objective. So, the seeding operation is critical; the tracers have to respect various conditions: not too small to be clearly "colour" recorded, not too big to follow the flow. In fact, these conditions are not more constraining as for standard PSV, PTV or PIV processes, but in RVV, they also have to be neutral in order to scatter the light without any wavelength change.

6. Colour image processing concepts in "rainbow volumic velocimetry"

Many image processing procedures dedicated to the quantitative analysis in fluid mechanics and to flow visualization have been proposed in the literature. However, on the contrary of the images recorded with the RVV technique, the images usually investigated are not colour images so that the classical techniques of image processing can be directly applied. In RVV, the governing parameter is colour (i.e. the wavelength) so its coding and analysis have to be considered with a particular attention. Therefore, a set of specific procedures has been developed allowing to extract quantitative information from colour images obtained with RVV. In fact, the whole process is divided in several steps including the image grabbing up to the rendering of the 3D velocity field:

- Image recording: As mentioned above, one has to place emphasis on preserving the colour information. Therefore, the image recording system, meaning the camera and the frame grabber, has to be selected with care. In fact, by now, among the various camera sensors available, no one can directly record the wavelength received. All sensors are sensible to a large wavelengths range which is limited by filtering. As a result, the more convenient cameras involve three CCD (3CCD) and register three images corresponding to three ranges of wavelengths. Consequently, with these 3CCD systems, the pertinent parameter that is the wavelength is lost and cannot be extracted directly. However, in the RVV technique, such a 3CCD colour camera (Sony DXC 990P) is used for registering images. The filtering used in this camera corresponds to the Red Green Blue colorimetric system and so the camera is associated with an RGB frame grabber. As a result, each image is stored as a 3D matrix (576×768 elements) that can be computed easily. Each pixel is characterized by three values corresponding to the R, G, B weights. Unfortunately, it is not possible to obtain the wavelength corresponding to these three values immediately. A practical approach consists in converting the RGB triplet in the HSL colorimetric system and to analyse the Hue value. In this way, an almost bijective relation between the Hue value and the wavelength (meaning the third coordinate in the thickness direction) can be obtained. However, only the central zone of the spectrum is correctly represented by this method, the external blue and red parts being described with a too low sensitivity.

- Image segmentation: The first operation when analyzing the images is to recognize, in each image, the different luminous segments corresponding to the tracers displacements in the flow (case of PSV). In the RVV application, the camera operates in an interlaced mode meaning the CCD array is divided into two fields grouping the even and the odd lines, respectively. In fact, the fields correspond to two images obtained by dividing the exposure time into two parts successively. So, foremost, the image is de-interlaced by simply merging the two fields without applying any interpolation or duplication that may modify the colorimetric properties. Then, the image is converted in the HSI system and a morphological (top-hat) transformation is applied to the Intensity image for extracting the particle traces from the background. Then the segmentation, characterized by a threshold level chosen by the experimenter [16], is followed by a morphological opening for removing small objects before a labelling procedure is applied. The extremity coordinates of each segment are obtained from the resulting binary image, while their colorimetric values are extracted from the initial image. At the end of this procedure, each streak extremity is characterized by its two coordinates in the image and its three colorimetric R, G, B values.
- Spectrum characterization: In order to reconstruct the third coordinate, the colour distribution within the rainbow volume has to be known as accurately as possible. Unfortunately, due to several technical reasons but also to the spectrum generation itself, the colour distribution within the lighting volume and especially in the area of interest cannot be assimilated to a mono-dimensional field of wavelength. As a result, an accurate calibration process is applied: it consists in placing in the studied zone a set of tracers fixed within a block made of a transparent material. Then, by simply moving this block and using the same tracers to those used for seeding the flow, it is possible to simulate the whole image acquisition process. In addition, the position of the particles within the block being known, this process permits to obtain a set of data representing the colour distribution in the whole lighting volume. Lastly, an automated process driving simultaneously the frame grabber and a three micrometric stage provides a "colorimetric matrix" which characterizes the colour distribution.
- Determination of the depth position: At this step, the data supplied by the segmentation can be interpreted thanks to the colorimetric matrix. The principle consists in selecting a particular axis within the colorimetric matrix corresponding to the image coordinates of the considered streak extremity. Then the data along this axis are fitted with three cubic spleen functions corresponding to the Red, Green and Blue stimuli in the RBG colour space. Finally, the depth coordinate of the considered extremity is computed by minimizing the Euclidian colorimetric distance between the spleen functions and the RGB values of the extremity.
- Determination of the three coordinates in the laboratory space: In fact, the principle of RVV requires to record images from a volume and not from a plane like in classical visualization techniques. As a result, the perspective effects cannot

be neglected and this becomes particularly important for a volume thickness greater than a few millimetres (between 10 and 30 mm in common RVV applications). Therefore, an additional optical calibration of the camera is required for reconstructing the actual tracers' positions in the laboratory space. A classic way to achieve this operation consists in applying a mathematical transformation that can be summarized in a "perspective projection matrix" M whose inversion allows obtaining the three coordinates in the laboratory space.

- Velocity field: The last step concerns the computation and the representation of the velocity field. Considering the two extremities of a particular luminous streak, one can easily obtain the displacement of the considered tracer that occurred during the exposure time and consequently the corresponding modulus of the local velocity. The very last point to be solved is the ambiguity on the flow direction. In the RVV process the use of a camera operating in the interlaced mode provides a way to introduce the temporal information needed to solve the problem. In fact, since with RVV the particles stay in the lighting volume during all the exposure time (the others are easily detected and removed from the analysis), each luminous streak can be divided into two parts, the first one corresponding to the even field and the second one to the odd field. Finally, one streak extremity is registered in the even field while the other is in the odd field. This additional information is used for obtaining the local flow direction.

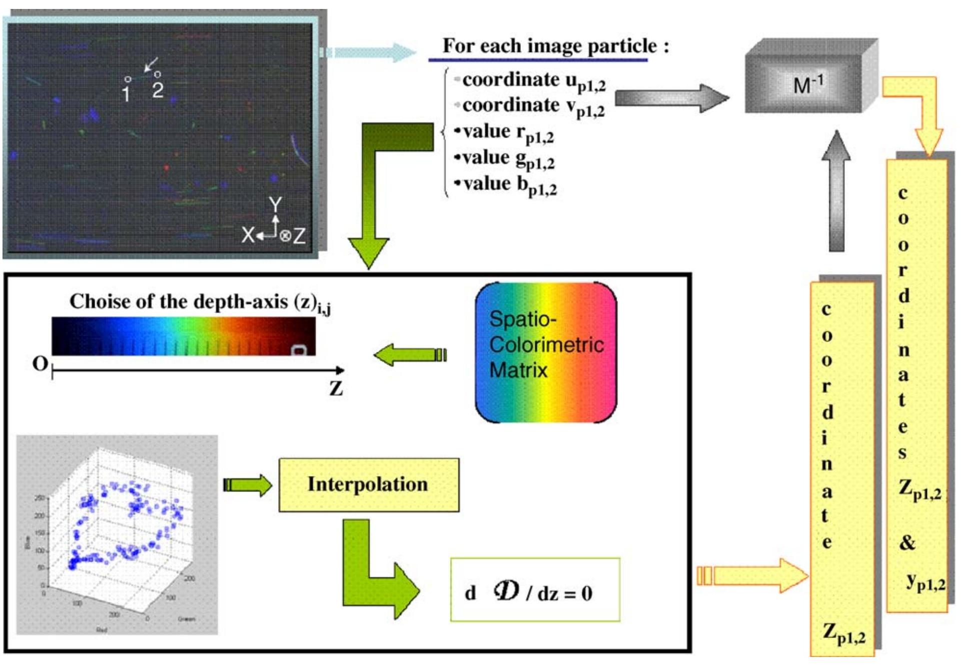


Fig. 6. RVV image processing.

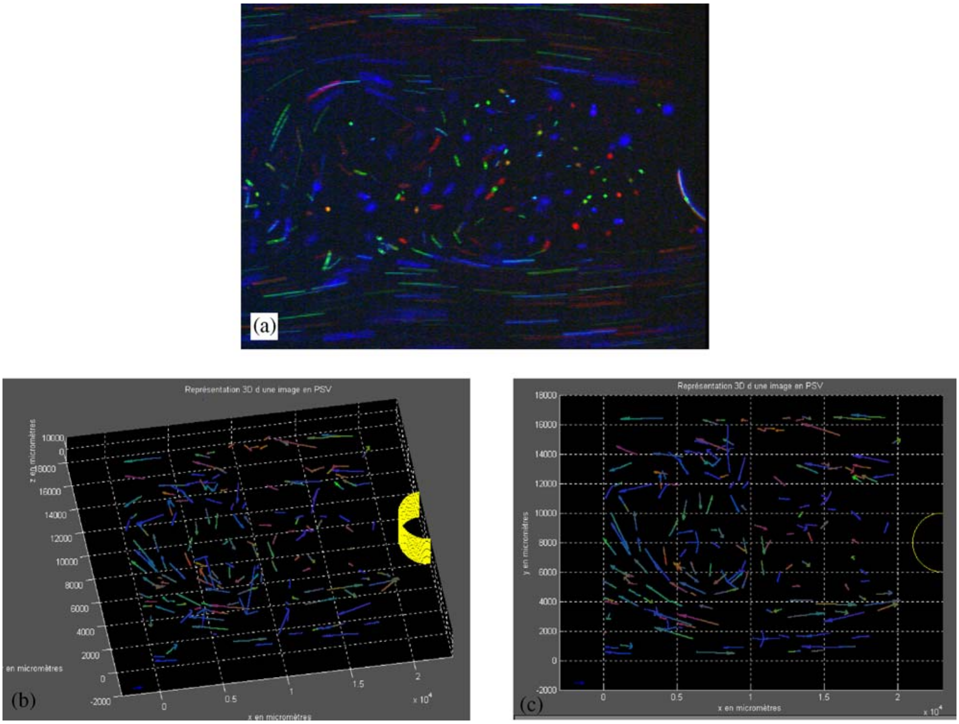


Fig. 7. RVV in the wake of a cylinder ($Re = 300$)—visualization (a), 3D3C velocity field (b) and 2D3C velocity field (projection) (c).

The global process relating to the image processing presented above is reported on Fig. 6. A typical image obtained by means of RVV in the wake of a cylinder for a Reynolds number about 300 is shown on Fig. 7a (the main flow is from the right to the left). Some luminous streaks are quasi-monochromatic indicating the flow is locally 2D. Others are polychromatic, so the flow is locally 3D. The 3D velocity field can be extracted in the whole volume as presented on Fig. 7b.

7. Conclusion and prospects

The light used as a sensor is a very interesting tool for experiments in fluid mechanics and numerous flow visualization techniques have been proposed since the last decades. The single plane laser sheet is commonly used for qualitative and quantitative investigation. Many improvements in image analysis have led to accurate measurements principles like PSV, PTV, and above all PIV nowadays. However, the problems investigated are more and more complex. In addition, the recent improvements in numerical simulations allow to compute some 3D flows and also

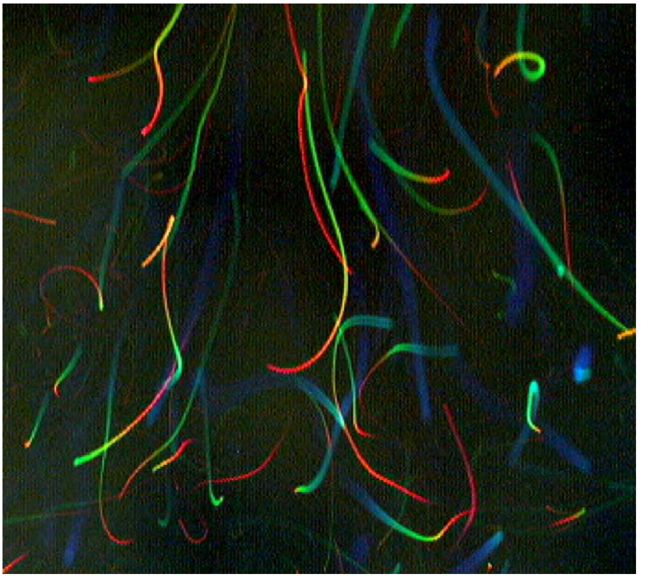


Fig. 8. 3D trajectography by means of RVV.

some 3D and non-stationary flows. Consequently, these numerical approaches need to be confirmed and validated by experimental measurements. Therefore, different solutions have been proposed in the literature: the most advanced is certainly the stereo recording, permitting to obtain the three velocity components near the lightened plane; another one is the holographic technique allowing to reconstruct the position of each tracer in a volume but its performances are strongly limited by the cameras resolution. In both cases, a pulsed illumination is used in order to ‘‘freeze’’ the flow. The evolution of the single plane tomography up to the RVV as exposed by the authors in this paper does not follow the same concept: here, the goal is to obtain a technique capable of measuring the three velocity components in the whole lighted volume leading to 3D–3C investigations. In addition, thanks to a volumic lighting, actual trajectography can be performed by using a long exposure time (Fig. 8) or by considering the same tracer movements in a set of successive frames.

In the near future, the authors intend to improve the different parts of the RVV process. Indeed, many progresses remain possible especially concerning the light source which intensity could be increased easily by using a more powerful discharge lamp. Besides, the image processing procedures currently used are still in development in order to reduce the computing duration and to obtain an actual industrial tool for 3D–3C velocity measurements.

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