PALLAS, a Novel Experimental Concept for Flow Diagnostics

István GORICSÁN, János VAD, Balázs TÓTH
Department of Fluid Mechanics, Budapest University of Technology and Economics
Pál GREGUSS
Department of Manufacture Engineering, Budapest University of Technology and Economics

Abstract

The paper presents a novel laser optical method offering a potential for qualitative flow visualisation as well as for quantitative fluid mechanical studies. Such quantitative experiments regard measurement of fluid velocity and concentration distribution of light scattering objects. The proposed concept is based on a Centric Minded Imaging (CMI) methodology ensuring a full 360° angle panoramic view information instead of the conventional "see-through-a-window" concepts having a limited range of view angle. The presented CMI optical system comprises a Panoramic Annular Lens (PAL) optical detection unit and a LAser Sheet illumination equipment abbr. PALLAS system. The potential advantages of CMI methods applied to flow diagnostics are discussed in the paper through the example of the PALLAS system. This paper provides an introduction to the optical flow diagnostic based on laser sheet technique by means of summarising the basics of Particle Image Velocimetry (PIV) and laser sheet concentration measurements.

1 Introduction

In the past years, the laser sheet (LS) technique, complemented with an appropriate detection system and digital image processing procedure appeared as a powerful tool for high-resolution tomographic mapping of fluid flow. Such experiments are carried out in order to obtain qualitative information (visualised flow) as well as quantitative information (velocity field, seeding concentration field) on flow characteristics. The LS technique finds its application in several areas of experimental fluid mechanics. Examples for such applications are: qualitative flow analysis [1], measurements of oil smoke concentration distribution in wind tunnel modelling of air pollutant transport phenomena [2], or particle image velocimetry for complex velocity and turbulence field studies [3][4].
The use of these advanced experimental methods is reasonable when their advantages in comparison with traditional measurement techniques counterbalance the significantly higher expenses of instrumentation.
The laser-based techniques are characterised as follows:

- Not a solid state measurement device but an "optical probe" of high intensity laser light is introduced in the fluid under investigation, avoiding disturbance on the flow field.
- With the use of appropriate transmission optics, high focusing of the laser light is carried out, and the extension of the optical probe is considerably reduced. Accordingly, the laser-based techniques offer a possibility for measurements of high spatial resolution.
- The optical flow measurement techniques are based on detection of light scattered by microscopic objects moving with the fluid. Since the light scattering objects trace the flow, the scattered light provides relevant information on the flow properties. The flow information can be quickly obtained, according to the fast propagation of light, the applied fast response optical detectors, and the advanced electronic data acquisition and signal processing techniques. Hence,

measurements of high temporal resolution and high data rate can be carried out.

- Depending on the structure of the optical probe, components of vector quantities (velocity field, displacement field) and their signs can be distinguished in measurements, ensuring directional sensitivity.
- Since the calibration factors for these techniques are known and relatively stable (depending on constant optical and geometrical parameters), the calibration process for laser based measurements is simple or can be ignored.
- In certain cases, the optical probe can be used at a large distance from the experimental equipment. Hence, spatial zones can be probed which are normally accessible with difficulty or inaccessible for traditional measurement devices. This arrangement provides a means for remote measurements.

The use of laser-based techniques is ideal for the following on-site measurements and laboratory applications:

- Determination of high-resolution accurate flow data providing a basis for boundary conditions used in CFD, for the verification of CFD results and for improvement in CFD codes.
- Fast, accurate and convenient on-site calibration of traditional measurement devices.
- Comprehensive experiment-based preparation for the selection of special air handling system elements.
- Convenient methods of studying flow characteristics related to structural elements that are accessible with difficulty for traditional measurement devices.

For the investigation of airflow, air-particle and air-droplet systems (dusty and humid air) and the related technical equipment, laser-based techniques fulfil the following experimental demands:

- flow visualisation;
- velocity and turbulence measurements;
- particle and droplet size distribution measurements;
- particle and droplet concentration measurements;
- simulation of transport and measurement of concentration distribution of air pollutants;

2 Laser sheet (LS) technique

A thin laser "light sheet" of high intensity is produced with use of appropriate optics, by means of which an entire "slice" of the fluid flow is illuminated (probed). If a sufficient concentration of light scattering material such as oil smoke is ensured, the LS technique appears as a powerful tool for flow visualisation. Beside such qualitative studies, a quantitative, tomographic characterisation of the flow field can be carried out by recording and digital processing of the scattered image. Particle Image Velocimetry (PIV) supplies two-dimensional velocity data simultaneously in a planar flow section illuminated by the laser sheet. Another quantitative application of the LS method is the simulation of transport and measurement on the concentration distribution of gaseous or dusty air pollutants. If the dusty pollutant is present in the airflow at a high concentration, it appears as a "natural" multitude of light scattering objects. Otherwise, the flow must be seeded, simulating the dusty or gaseous pollutants being transported. The seeding particles or droplets must be capable of tracing the turbulent flow with high accuracy. Based on the analogy of turbulent mixing of gases, the seeding particle or droplet distribution corresponds to the gaseous pollutants in the actual application.

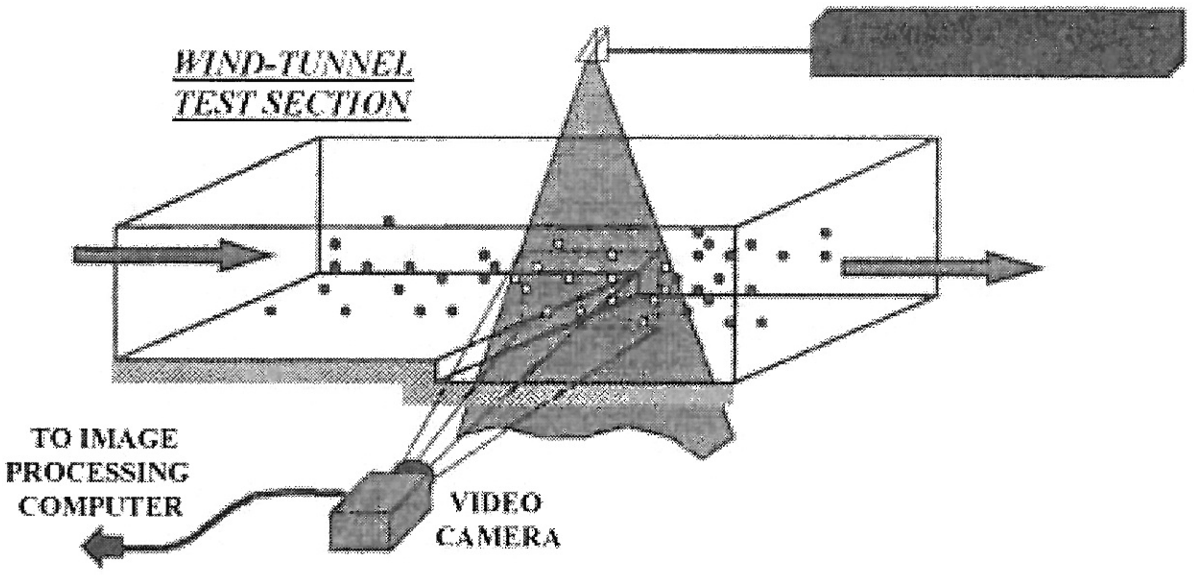

Figure 1. General set-up for LS measurements [13]

2.1 *PIV as a typical application of LS tecnique*

In case of Particle Image Velocimetry (PIV) measurements two images are taken from the same place and direction. Therefore there is only time interval between the two exposures. During this time interval tracers are moving with the flow. According to the displacement (Δr) and the time interval (Δt) the velocity can be calculated by the usual equation:

$$\underline{v} = \frac{\Delta \underline{r}}{\Delta t} \quad (1)$$

By PIV technique the two-dimensional, two-component (2D2C) velocity field of the flow can be determined. Nowadays there is a solution for measuring all the three components (2D3C) of the velocity field in the laser sheet. One of these techniques is called Stereoscopic PIV.

The basic equation of the speed calculation is (1). To measure velocity, relative displacement has to be computed. According to the duration and the value of the displacement, the direction and the magnitude of the speed can also be calculated.

To realise this kind of velocity measurement is quite easy as a typical laser sheet measurement. Two images are taken of the illumination laser sheet. The time interval between the two exposures gives the duration of the displacement. The magnitude of the displacement can be “measured”.

The images are broken into interrogation windows. The size of interrogation windows depends on the number of particles and the maximum displacement of the particles in the window. In most cases their size is 32x32 or 64x64 pixels.

Cross-correlation methods are now generalised to analyse the records. The maximum value of the cross-correlation of two functions gives a displacement value. Shifting the first function by this value of displacement results the superpose of the two functions.

$$W_a(x,y) \circ W_b(x,y) = C(x,y) \quad (2)$$

In practise the two functions (“W_a(x,y)” and “W_b(x,y)”) are matrices containing intensity information of each pixel of the two images or specified the two corresponding interrogation windows. The place (“(x,y)”) of the maximum value of the cross-correlation function (“C(x,y)”) defines the displacement.

Finally the velocity can be calculated from the displacements. The velocity vectors connected to the different interrogation windows describe the velocity field of the inspected area.

2.2 *Laser sheet concentration measurement*

In case of optical concentration measurement the measuring apparatus is naturally the same as applied in case of PIV measurement. Scattering particles - which can follow the flow proportionally to the pollutant - are seeded into the flow, which is illuminated by a laser sheet. A photo is taken from this light plane. The difference is only in the way of digital image processing.
During the measurement the intensities of certain pixels of the image are proportional to the numbers of particles at the appropriate area of the light plane. The number of particles at the appropriate area of the light plane is proportional to the concentration of the pollutant. That is why theoretically according to the image the concentration distribution could be determined immediately in the field of measurement. However in practise diverse corrections are needed to make the result adequate to the real case.

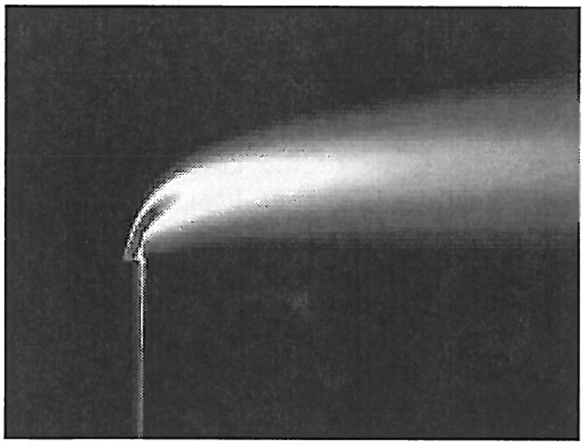

Figure 2. Photograph to the optical concentration measurement

3 PALLAS as a novel experimental concept for flow diagnostics

In conventional LS experiments, the laser sheet-generating unit is usually placed above the test section and the optical axis of the camera is adjusted more or less normal to the laser sheet. The scattered light is received by the detector optics front surface of limited aperture. This "see-through-a-window" detection arrangement results in considerable limitation in view angle even if a fish-eye optics of increased view angle is used. In this configuration, the sideward-scattered light coming from the tracer particles is detected by the camera. Since the sideward-scattered light of a spherical scattering object has generally the lowest intensity, the conventionally used LS+DIP technique necessitates the use of a high-power illuminating laser source. In conventional arrangements shaded flow zones may appear, making impossible the mapping of velocity and concentration field just in the vicinity of the obstacles, which would be especially important in investigation of boundary layer flow.

The mapped (imaged) flow zone is limited by the image area of the camera optics, limiting the experiments to only a part of flow field. The illumination and detection units are separate, making impossible the elaboration of a small-scale, mobile, compact experimental device and raising fine mechanical problems in simultaneous positioning.
Recently, a novel experimental concept has been outlined at the Department of Fluid Mechanics, Budapest University of Technology and Economics for surmounting the limitations listed above and representing further advantages, thus supplying a potential for extending the applicability of LS techniques. The novel concept is based on the Centric Minded Imaging (CMI) technique [7] The CMI methodology ensures a panoramic view information on the scattered image of full 360° polar object angle, in contrast with the conventional "see-through-a-window" imaging manner. Such capability is achieved with inclusion of a Panoramic Annular Lens (PAL) [10][11] in the optical detection system. The PAL has already proved its suitability in optical systems of robotics, satellite based research, astronautics, endoscopic techniques, biology, medicine,

and other fields [8][9]. The longitudinal section and ray tracing of PAL are seen in Figure 3. However, by the authors' knowledge, no application of PAL has been reported so far in flow diagnostics.

As a tool for CMI application in flow diagnostics, an optical system called PALLAS has been established. The PALLAS system realises a concerted application of a PAL-based optical detection system and a LAser Sheet illumination unit. The PAL unit receives light scattered by seeding particles passing the laser light probe in the extensive spatial zone determined by the full 360° polar object angle and the azimuthal angular range characterising the PAL unit. The PALLAS system has been described and its potential advantages respect to traditional LS methods have been pointed out in [5][6].

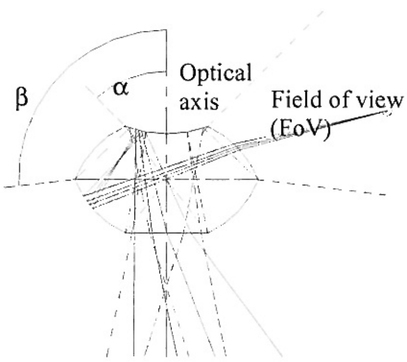

Figure 3. The longitudinal section and ray tracing of PAL

The main features of CMI methods are presented through the example of PALLAS system. The system as well as its potential advantages versus conventional LS tools are described in [5][6], so only a brief summary is given here.

Figure 4. shows the functional scheme of a fully developed PALLAS equipment. Since the PAL optical lens includes a blind zone not utilised in image formation, a miniaturised light probe generator can be integrated in the blind zone within the bulb of PAL. The proposed light probe generator realises a centric minded illuminating concept, in contrast with the traditional LS technique using a sectorial laser sheet. The integrated LS generating unit receives the light input through an optical fibre from an external laser source. The PAL, supplemented with auxiliary detection optics, transmits the image scattered by the multitude of seeding particles located within the spatial range of full 360° polar object angle.

According to this arrangement, a fully developed PALLAS equipment, based on the CMI concept, offers the following potential advantages versus a traditional LS technique involving the "see-through-a-window" detection methodology:

- the probed (imaged) flow zone can be extended due to the CMI concept;
- due to quasi-backscattering detection, a lower power laser source can be used;
- a small-scale, compact, mobile measurement device can be developed (integrated illuminating and detection functions);
- the disturbance of flow due to the measurement device can be fully eliminated;
- according to the centric minded, commonly centred illumination and detection optics, the shading effects can be avoided and thus, complex flow phenomena in the vicinity of solid boundaries (boundary layers) can be extensively studied.

In addition to these advantageous features, the following principles must be taken into consideration for judgement of general applicability of CMI concepts in fluid mechanical experiments:

- Although the planar laser light probe (laser sheet) is beneficial in most cases for tomographic mapping of fluid flow, specially shaped light probes can also be generated by means of the centric minded illuminating method. By means of the centric minded illuminating unit included in the PALLAS equipment, conical light probes can also be generated if they fit to the fluid mechanical problem to be investigated better than a planar LS.
- With appropriate seeding, data acquisition and data processing, the PALLAS concept representing CMI can be applied in

qualitative flow visualisation as well as in quantitative studies such as seeding concentration field studies, and particle image velocimetry for determination of velocity and turbulence characteristics.

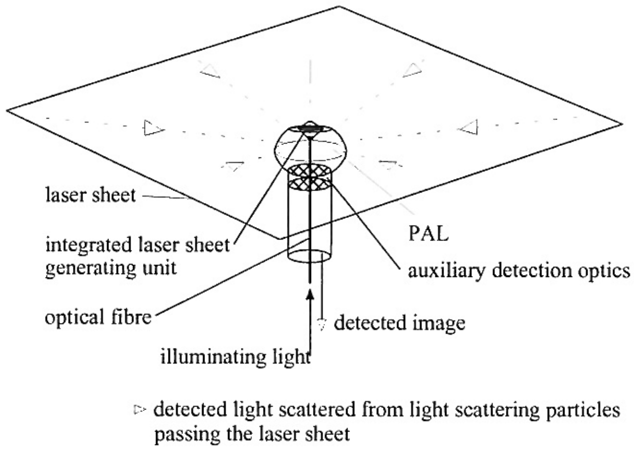

Figure 4. The functional scheme of a fully developed PALLAS equipment

As a step towards development of a mobile, miniaturised measurement tool, a small scale PALLAS detection probe has been produced. The probe connected to a CCD camera is shown in Figure 5.

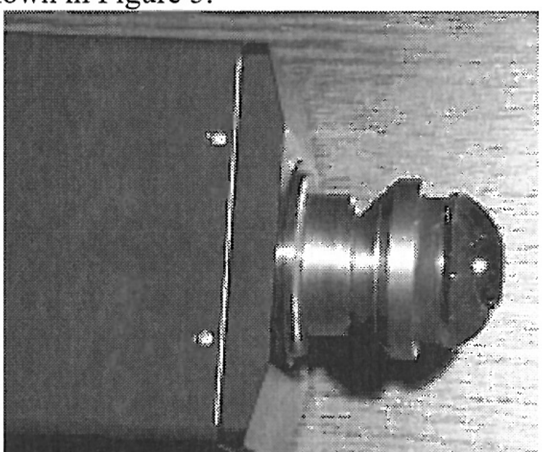

Figure 5. Miniaturised PALLAS detection probe

4 Digital Image Processing

In case of each LS technique digital image processing is necessary after taking a "photo". This procedure covers corrections caused by difference distortions. First group is the distortions derived from the illumination. The intensity distribution inside a light sheet would be homogeneous, although this can not be ensured. In general, the light intensity decrease far from the source, in case of large investigated area this decreasing would be considerable. Several sources of distortions exist considering the way of light sheet producing, which won't be discussed in the framework of this paper. The other group is the distortions due to the applied detection system, which contains the aberrations of applied lens and the distortions caused by different type of detection. In the latter case the intensity inhomogenity derived from the different angles of exposure, so called "view angles" .

Besides, in the case of CMI systems, an additional, usually computer-based image retransforming procedure must be applied to the detected (annular, panoramic) image in order to obtain a true object view.

A special procedure has been established and is under improvement for appropriate retransformation of PAL images scattered from a plane such as a LS light probe. The retransformation procedure comprises semi-empiric and analytical models for treatment of PAL imaging peculiarities. The PALLAS technique involves presently an advanced computerised image retransformation method. The scheme of CIM image formation and retransformation is shown in Figure 6.

If the PAL is situated inside of a cylinder in such a way that the optical axis coincide with the axis of the cylinder (see in Fig. 4 object space), the inner surface of a cylinder projected to a so-called circle picture (see in Fig. 4 picture space). The upper circle of cylinder is transformed to the picture as inner circle, the lower circle as outer cirle. The generatrix of cylinder denoted AB is transformed as a radius. It is apparent that M point which situated in the middle of AB section in the object space there is no in the middle of A’B’ section in the picture space (M’).

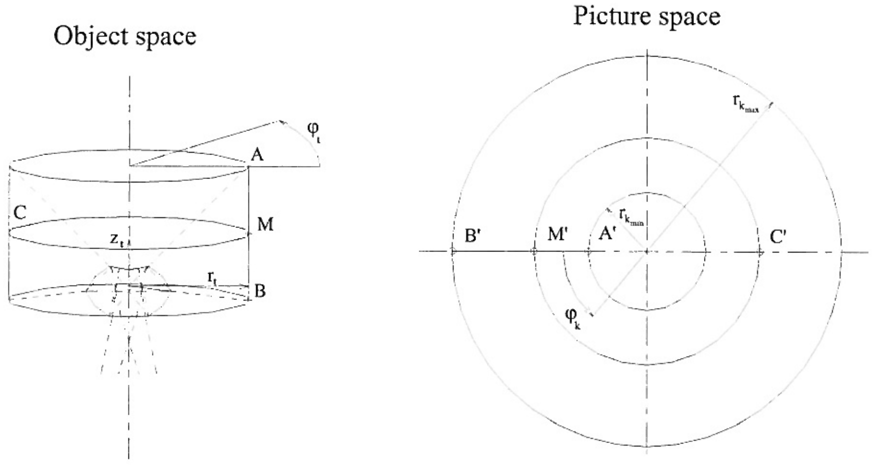

Figure 6. Image formation

$$\varphi_k = \varphi_t \qquad (3)$$

$$r_k = r_{k_{\min}} + \left[Ax^2 + Bx + C\right]\left(r_{k_{\max}} - r_{k_{\min}}\right)$$

$$x = \frac{-z_t + \dfrac{r_t}{\operatorname{tg}\alpha}}{\dfrac{r_t}{\operatorname{tg}\alpha} - \dfrac{r_t}{\operatorname{tg}\beta}}$$

$$A = 0.2424$$

$$B = 0.6421$$

$$C = -0.0014$$

The applied cylindrical co-ordinate system is seen in Figure 6. In the object space the co-ordinates are denoted r_t, φ_t, z_t in the picture space in turn r_k, φ_k, z_k. The transformation function of PALLAS optical system contained PAL and an auxiliary lens is shown in (3). The constants A, B and C depend on the applied optical system. In case of different arrangement mentioned above first the co-ordinate systems of object and image space must be transform into each other.
Since the spatial resolution capability of PAL is depend on distance from the origin in non-linear way, an effective investigated area can be defined. Applying the PIV technique it is very important to allow the individual particles shown in the image to be able to determine their displacements accurately. Whereas in case of concentration measurement it should endeavour to suspend as much particles as possible – complying the similarity laws of spreading- to get as high intensity values as possible procedure. The number of particles belonging to a pixel must be at least 1. When this criterion is not fulfilled, the measurement set-up should be modified. Either the number of particles should be increased or a smaller field of view should be applied either by moving the camera closer to the light plane or the objective of the camera should be changed.

5 Summary

General applicability of centric minded imaging (CMI) techniques applied to fluid mechanical studies has been discussed in the paper. Such techniques, possibly together with application of a centric minded illuminating concept, present a number of potential advantages making possible an extension in application of laser optical flow diagnostics. The PALLAS measurement system, based on the CMI concept, has been presented in the paper and some improvements in the PALLAS technique have been reported. For application of CMI methods in flow diagnostics, a patent has been filed.

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