A weather independent illumination for field LSPIV

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Abstract Large Scale Particle Image Velocimetry is a further development of PIV dedicated to measure the surface velocity of flows, in particular of rivers under field conditions. This paper addresses the problem of illumination which is the bottleneck of the technique at the present time. Using a pulsed high efficiency LED together with adapted collimation optics the light intensity obtained is higher than that of daylight for a modified schlieren set-up, which detects the undulations and curvature of the river surface under specular reflection. The undulations thus serve as natural tracers for the PIV algorithm. The set-up uses retro-reflective fabric to send the light from the LED back into the camera with a high efficiency. The set-up is self-collimating due to the properties of the fabric, which is placed on the opposite bank of the river. It is compact and delivers images for large fields of view even at night. The resulting images are orthorectified due to the small angle of incidence of the optics on the river surface. The images allow PIV evaluation giving a large number of valid vectors even for one image pair. Due to the ease of installation the set-up is well fitted for monitoring rivers under most conditions even at night.

1. Introduction

Large scale particle image velocimetry (LSPIV) is a field application of PIV used to measure the 2d velocity of the surface of flowing water, e.g. the surface of a river. With the increasing need to monitor river flows, due to climatic changes LSPIV has the advantage that it is relatively cheap to implement and that even under conditions that endanger human life such as floods images can be obtained automatically delivering information that could be life saving. The initial idea was developed by Fujita in 1994 [1]. It uses image patterns at the water surface as tracers. These can be any floating pieces of wood, ice, foam or surface waves seen under specular reflection. These waves can result from turbulent structures within the flow. Other authors actually seed the flow with floating particles. However, no matter what type of tracer is used “the most challenging problem for implementing LSPIV in field conditions, …….., is attaining a good visualization of the stream free surface”, [2]. Normally images at river locations are taken during the day when illumination conditions are more favourable. Especially if specular reflections are used to utilize the natural tracers of the water surface the illumination conditions are a matter of luck. The advantage of using undulations of the surface is that they, if present cover most of the surface under surveillance allowing an efficient image evaluation. The aim of the present paper is therefore to develop an illumination that allows under field conditions to obtain specular reflection images of river surfaces at any time without having to hope for the right weather.

2. The basic concept of LSPIV

Figure 1 shows four consecutive images of a river surface taken at ten frames per second using daylight for illumination. The images show two types of tracers that can be used for LSPIV. Some patches of foam can be seen floating past as well as some specular reflections. However, the both the framing rate and the tracer density are too low for cross-correlation evaluation. One can obtain some surface velocity values using particle tracking algorithms, but these are not sufficient to make a representative profile of surface velocity across the river. It would need a large number of image
pairs to meet these requirements. Two conclusions can be drawn from these images. The frame separation has to be lower and more tracers are needed.

Suppose the surface velocity distribution across the river has been measured and the cross-section of the river is known, obtained by bathymetry for example. There is a quasi-empirical relation between the depth averaged velocity and the surface velocity. If the surface of the river bed is smooth or has a well defined and regular roughness the vertical velocity profile from the surface to the river bed could be derived from hydrodynamics. However, this is almost never the case and an empirical coefficient $k$ is used that couples the surface velocity to the depth averaged velocity. The value of $k$ varies between 0.789 and 0.928, see [2]. Higher values are found for deep rivers with smooth beds. Typically the value of 0.85 is used to calculate the depth averaged velocity at each point. Its area integration over the river cross-section delivers the discharge. This presumes that the shape of the vertical velocity profile is similar across the river.

Figure 1: Sequence of images of the surface of a river taken at ten frames per second using daylight for illumination.

Muste et al. [2] present a review of the application of tracerless LSPIV to the Iowa river during normal flow and floods and compare the results with Acoustic Doppler Current Profilers. The acoustic measurements require deploying personnel and equipment on boats, which is prohibitive during floods.

At each location the measurements of stage and discharge of the river deliver a curve which is representative for the river at this location during normal steady flow. However, during floods the behaviour shows hysteresis. The discharge is higher for the same stage during rising of the water level and lower than for the same stage for normal flow conditions when the flood recedes, unsteady flow. The steady state curve has to be extrapolated to the flood conditions. It is therefore desirable to measure discharge also during transients in order to predict the flow downstream for
example to warn and to prepare the population, i.e. an automatic measurement method that can function under almost all weather conditions, the exception is thick fog.

In the following the basic idea for illumination is described starting from a schlieren set-up and applying different measures that allow measuring large fields of view.

3. Morphing a schlieren set-up

Starting point of the explanation is a classical schlieren set-up at the top of Figure 2. The second step is to fold the set-up on itself by using a mirror with a small tilt of the optical axes. The third step is to shift the mirror closer to the lens and to position the phase object in front of the lens. The combination of lens and mirror can now be replaced by a retro-reflective foil or fabric in a last step, provided the tilt angle of the optical axes fall within the range of acceptance of retro-reflective fabric. These fabrics are used as stripes on the clothing of firemen or workers on highways or as...
foils on the traffic signs. When a light source illuminates a retro-reflective foil the light is sent back more or less in the direction from which the light originated. Therefore, within a region around the light source the light is recollected and this does not depend on the precise angular position of the RRF, Figure 3 dashed. The advantage is that the intensity of reflected light is very much higher than a white scattering surface allowing visibility for large distances.

The advantage of using RRFs is that now no large field lens or curved mirrors are needed any more and a schlieren set-up can now have a very large field of view. Weinstein and Settles developed at Penn State University a full scale schlieren system, see e.g. [3]. They use a retro-reflective foil (RRF) from 3M for illumination, with a size of 5.11 m x 4.08 m.

A schlieren set-up is sensitive to the integral of refractive index gradients along the optical path of a light ray. These gradients deflect the light due to refraction. More or less light reaches the camera depending on the direction of deflection. In figure 2 a downward deflection would reduce the intensity since it would be partly stopped by the schlieren edge. The schlieren edge is positioned at the point where an image of the light source is produced. In reality the light source is not infinitely small. Thus the result of deflection is not complete blocking of the light. As a matter of fact the edge does not have to be an edge. It can be the iris stop of the optics on the camera. This configuration is used for the LSPIV application shown on figure 3.

This set-up is a two pass configuration. The light coming from the light source is reflected specularly on the surface of the river and reaches the RRF where it is sent back in the same direction. Once again the light is reflected at the surface of the river and thus reaches the camera. Undulations of the water surface deflect the light and depending on the size of the stop of the lens on the camera will reach the CCD chip or not. This is basically the set-up for the schlieren system described above, however the light deflection comes from the surface undulation and not from refractive index gradients. The curvature of the water surface will spread or concentrate the light beams thus giving a further modulation of the light intensity reaching the CCD camera. In the present case not a foil on a plate was used as in [3], but a retro-reflective fabric Type 8925 from 3M. This fabric is washable, thus adapted for field use and can be rolled allowing for transport. It is produced in large widths (> 0.9m) on roll lengths of 50 and 100m. In the present case (proof of principle) only small pieces of 1 m² were used. The enormous advantage of using RRF is that the optical system is self-adjusting. Only the size of the RRF has to be sufficient for the field of view. Fortunately, due to the small angle of incidence of the optical axes on the river surface the height of the RFF not have to be very large although the surface area covered by the images can be very large. Figure 4 shows images of the set-up as positioned on a small river for different exposure
conditions with a wide field of view and not synchronised with the flash. One can see both the camera with lens and the light source as blurred objects mounted on a tripod. At the opposite side of the river the RFF can be seen as a square. It hangs on thin ropes from the balustrade of the embankment on the opposite side of the river. At the bottom side of the RFF a metal stripe keeps the RFF stretched. This is only an example of a simple way of mounting the RFF.

On the images taken with a separate camera already the effect of the RFF can be seen on the river surface. The specular reflections are strongly enhanced. The image with a short exposure shows that the light intensity of the light source is higher than that of daylight.

![Daylight](image1.png) ![Daylight and Flashed Light Source](image2.png)

![Daylight and Flash, Long Exposure](image3.png) ![Daylight and Flash, Short Exposure](image4.png)

**Figure 4:** Pictures of the set-up as positioned on a small river.

### 3. The light source

The light source is a pulsed LED from Luminus SST90. Under steady state conditions it delivers 1000 Lumen. When pulsed for 100µs with 80 ampere the intensity delivered by the LED is seven times higher. However, the emission of the LED covers a large angle. A Total Internal Reflection Reflector and a lens (f=90 mm, d=50 mm) collect the light from the LED giving an illuminated spot with a diameter of 3m at a distance of 15 m, figure 5.
The driver of the LED is a simple circuit that has a TTL input that drives an appropriate power MOSFET. The high current is delivered by capacitors. The mean current load on a battery is therefore about 200 mA for 20 flashes per second. This allows obtaining long sequences of images without having to transport a heavy battery.

The flash is synchronized with the camera. In a first measurement campaign images were taken at 15 frames per second, due to the USB camera in use, Blue Fox from Matrix-Vision. However, this frame separation is not sufficiently low for evaluation. In a second campaign frame straddling is used allowing any frame separation down to the width of the light pulses, i.e. 100 \( \mu \)s. Frame straddling has however the disadvantage that the second image of the pair is integrated for the duration of the transfer of the images out of the camera. Therefore a camera with a framing rate in the order of 100 frames per second is recommended to keep the integration time short. In our case the camera had a framing rate of 15 frames per second. Therefore the images were taken at dusk and at night to reduce the effect of daylight on the second image. With a camera with a higher framing rate the images can be taken at any time.

3. Results

Figure 6 shows a raw image pair taken at a separation of 6 ms. The field of view is 3 m at the top of the image and much less at the bottom of the image due to the small angle of inclination of the optics relative to the river surface. The images have to be orthorectified. This is a linear transformation that converts the pixel coordinates to real world coordinates on the river surface, see e.g. [4] using known markers on the images.
Figure 7 shows an orthorectified image pair of the reflecting river surface. The images have been rotated to fit better into the format of this paper. The flow is now from top to bottom. The image shift is too small to be detected by the eye. Structures in a large range of sizes can be seen on these images. They reflect the turbulent nature of the flow. The larger structures are upheavals of fluid coming from the bed of the river and are not localized as would be the case when a large stone disturbs the flow. The image shift can be seen on excerpts taken from both images, but also here the shift is in the order of a few pixel.

The images have been evaluated using a cross-correlation algorithm. Figure 8 shows exemplarily the evaluation of only one image pair with interrogation areas of 32 x 32 pixel, and 75% overlap. Outliers have been filtered out with a velocity window and with a signal to noise ratio criterion. The seeding density obtained by the optical set-up is sufficient to resolve structures on one image pair. Therefore, one can actually study the development of structures as they cross the field of view. This opens the possibility of studying turbulent structures at the surface of a flow under field conditions. An analysis of their structure together with their velocity field can be performed.

The aim of the present paper is to present the technique and not to concentrate on the results that would need a more elaborate paper.
3. Conclusions

The complete set-up is composed of a pulsed LED, collimating optics, a CCD camera with lens, both mounted on a tripod, a small box containing the electronic driver for the LED and a 24 Volt battery with 2 ampere hours capacity, a lab-top and 2 square meters of retroreflective fabric. The set-up can be put into a suitcase for transport. It can deliver hundreds of image pairs, depending on the size of the RAM memory of the lab-top. The resulting images are well fit for cross-correlation evaluation with a high seeding density and resolve the surface flow allowing not only reliable average measurements of the surface velocity but also a temporal resolution of the flow. The energy requirements are low enough that in principle the energy could be obtained with solar panels when only images are needed every few minutes as is the case in river monitoring. The total costs are not high so that many monitoring stations could be installed allowing a coverage of a whole river basin.

References


