A Fast Multiple Shutter for Image-Based Metrology

Reinhard Geisler
Institute of Aerodynamics and Flow Technology,
German Aerospace Center (DLR), Göttingen, Germany
Reinhard.Geisler@dlr.de

Abstract A new mode of operation for CCD image sensors is presented, which is able to capture two short exposed frames in fast succession. An additional third frame can be captured with a long exposure time analogue to the well-known ‘double shutter’ mode. For the double-frame application, the data rate of this new mode can compete with – or even outperform – the fastest high-speed image sensors commercially available today. Image based measurement techniques such as Particle Image Velocimetry (PIV) will benefit from this mode when applied in bright environments. The third frame is valuable e.g. for acceleration measurements, advanced PIV evaluation schemes, or for particle tracking applications.

1. Introduction

The success of particle image velocimetry (Willert & Gharib 1991) as a well-established standard tool for flow investigations is closely connected to the development of digital cameras. Early applications with photochemical cameras provided high-resolution results, but suffered from ambiguities due to the double-exposure technique and furthermore, the cumbersome and time-consuming wet chemistry inhibited a fast evaluation of velocity vector fields in statistical significant numbers. With the advent of standard video cameras and fast frame grabbers these obstacles vanished (Lecordier et al 1994). Progressive scan cameras finally enabled fast measurements with sub-pixel accuracy free of artifacts caused by the interlace technique (Lai et al 1998). Current standard PIV cameras contain the so called ‘double shutter’ technique, which captures two frames in fast succession. The exposure time of the first frame is pre-selectable and can be considerably short (lower microsecond range). In contrast, the minimum exposure time of the second frame is limited by the readout time of the sensor (millisecond range). In typical PIV experiments, illumination is provided by pulsed light sources such as lasers. Hence, the long second exposure time is of no concern as long as the background illumination is kept dark enough. However, in some applications the presence of daylight cannot be avoided or the experiment itself involves luminescence such as plasma or combustion measurements. In these cases, the image information of the second frame is superimposed by this background illumination. As a result, the signal-to-noise ratio and finally the evaluation accuracy are reduced. In the extreme case, the image signal saturates, the relevant information is lost and an evaluation is impossible.

Different approaches have been proposed to tackle this problem. External shutters are either to slow (mechanical systems) or affect the image quality (electro-optical systems). Cameras with several image sensors sharing one lens by means of beam splitters can record short exposed frames in fast succession (Raffel et al 1995, Willert et al 1996). Unfortunately, they reduce the light available to the individual image sensors. Moreover, they require an additional effort to calibrate and maintain sub-pixel accurate image matching since de-calibration due to vibrations or temperature changes will directly bias the measurement results. Similar problems arise in the use of multiple tomographic systems (Lynch & Scarano 2013, Schröder et al 2013). Using a single image sensor with a modified version of the interlace technique (Parks 2009) is another option. Here, every second image line is left light insensitive and the consecutive frames are recorded with an offset of one line, both of which are not suited for sub-pixel accurate measurements. Finally, special image sensors for high-speed video cameras, fast framing cameras (Etoh & Mutoh 2005) or time-of-flight cameras provide only low resolutions at high frame rates and last but not least suffer from high costs.

The new solution presented here (framing-optimized exposure, FOX) takes advantage of standard
CCD-sensor properties (Geisler 2014). Deviating from the specifications provided by the sensor manufacturer, the image sensor is operated in a mode suitable to capture two frames in fast succession, both with a typical exposure time below 20 µs. In a binning-like process two neighboring pixels are combined to halve the space required in the light-insensitive vertical shift register. As a result, two frames can be stored in this fast local storage in a line-interleaved pattern. While the two interleaved frames are read out, a third frame can be captured with the full resolution and an exposure time defined by the readout time – a ‘triple shutter’ analogue to the well-known ‘double shutter’ mode.

2. Methods: The Framing-Optimized Exposure (FOX)

In the normal operation of an interline transfer CCD image sensor, prior to the exposure all charges are drained from the photo diodes. At the end of the exposure, the photo electrons released by the incident light are transferred into a light-insensitive local shift register (Figure 1 a-c). For each photo diode (pixel), a separate register cell is provided. One by one these charges are shifted towards an output amplifier and finally digitized by an analog-to-digital converter (Figure 1 d). During this time-consuming process, the photo diodes continue to collect photo electrons. Once the readout is complete, these charges can also be transferred to the shift register and read out (Figure 1 e-f). In the result, a second frame has been captured with an exposure time equal to the readout time of the first frame. This technique is commonly known as ‘double shutter’ mode.

The new fast shutter technique (FOX mode) is using the very same sequence for the first frame. The charge transfer to the light shielded register (Figure 2 a) terminates the first exposure time. Since this transfer is very fast, the temporal overlap of the two frames, which defines the minimum delay between the two illumination flashes, is considerably short (typ. 200 ns, the same as in the ‘double shutter’ mode). In the next step, only the register cells of every second pixel line are shifted (Figure 2 b). As a result, the charges of two neighboring pixels are added within the shift register and every second register cell is left idle. The charge of every second photo diode is then transferred into these register cells thus terminating a second exposure time for every second pixel line (Figure 2 c). Next, the complete register is shifted by one line (Figure 2 d) and the photo electrons from the remaining pixel lines are added to the shift register (Figure 2 e). As a result, two frames of short exposure time are stored in a line-interleaved pattern inside the shift register. Finally the shift register is read out in the common way (Figure 2 f) and the interleaved frames can be separated and be further processed by software. As an option, the charges accumulated during the readout time can as well be transferred to the shift register and read out. This provides a third frame at the full sensor resolution — a ‘triple shutter’ analogue to the ‘double shutter’ technique.
A sketch of the new timing is depicted in Figure 3. The exposure time $t_1$ for the first frame starts after the charges are drained from the photo diodes and ends with the transfer to the shift register. In contrast, the second exposure time starts immediately after the first one and is divided into two parts: First, the exposure time $t_2$ of the odd numbered lines terminates. The even numbered lines have a longer exposure time since the time $t_{2a}$ is required to shift the register by one pixel position (compare Figure 2 c-e). This difference in exposure time is typically no issue since the illumination is provided by a pulsed light source such as a laser.

However, it has to be guaranteed that the illumination flash for the second frame stays within the exposure time $t_2$. The optional flash for the third frame in turn has to be delayed until the end of $t_{2a}$ to ensure a correct exposure within the (long) exposure time $t_3$. In case the requested time delay $\tau_1$ between the first two flashes is longer than the exposure time $t_2$, an explicit dead time can be inserted (Figure 4) to keep the second exposure time short. In any case, the exposure time for the first frame can be set to equal the effective exposure time $t_2 + t_{2a}/2$ of the second frame to maintain identical ambient light levels in the both frames.

In conclusion, the new fast shutter (FOX mode) is capable of capturing two frames of short exposure time in fast sequence. The frames have a binning-like reduced vertical resolution, use the complete light sensitive area of the sensor and are completely congruent. As an option, a third frame can be captured (‘triple shutter’) analogue to the well-known ‘double shutter’ technique.
3. Examples and Discussion

The features of the FOX mode are demonstrated using a 4 megapixels prototype camera (reduced to 2 megapixels in FOX mode). The first exposure time is set to $t_1 = 15 \mu s$ while the second exposure time is $t_2 = 66$ ms in ‘double shutter’ and $t_2 = t_{2a} = 10 \mu s$ in FOX mode.

![Image of FOX mode example](image)

The first demonstration object to capture with the camera is a disk with 20 mm diameter rotating counter clockwise at about 30000 rpm. A random-dot pattern is printed on the disk to enable a cross-correlation analysis of the recorded motion. Illumination is provided by a LED emitting short (500 ns) light flashes at a temporal separation of 20 $\mu s$. In addition, the setup is illuminated by the ambient light usually present in the laboratory. The camera is synchronized to the LED flash and used to record the disk in ‘double shutter’ as well as in FOX mode for comparison. With the first frame of the ‘double shutter’ mode, a reasonable snapshot of the object can be taken (Figure 5 a, left). In the second frame, the accumulated ambient light results in a blurred image much brighter than the first frame (Figure 5 b, right). The striking difference in the dynamic range of both frames requires the images to be printed with a different brightness scale (compare Figure 5 a/b). Under the same illumination conditions, first and second frame from the FOX mode both show the same good snapshot quality (Figure 5 c). Despite the high velocity of about 40 m/s at the outer radius only a small displacement is visible between the frames corresponding to the time delay of 20 $\mu s$. 
For better visibility, a magnified representation of the same selected area is depicted for both frames in their lower left side (Figure 5 c).

A demonstration of the ‘triple shutter’ option is shown in Figure 6. Here, the environment has to be darkened to prevent ambient light from accumulating in the third frame. A total of three frames are captured in fast sequence, flash-illuminated at a temporal separation of again 20 μs each. The option to insert an explicit dead time not only can be used for flash-illuminated recordings but moreover, it can be used as a kind of ‘two-frame high-speed camera’. An example for such an application is depicted in Figure 7. Here, a common torch is used for continuous illumination. Again, the exposure time is \( t_1 = 15 \, \mu s \) and \( t_2 = t_2a = 10 \, \mu s \). The dead time between the frames is set to 35 μs. With these settings, the movement of the fast spray particles can be analyzed without the need of a flash illumination.

Finally in Figure 8, PIV-evaluations of a free turbulent jet flow simultaneously recorded with a ‘double shutter’ and a FOX mode camera are compared. Both cameras use identical lenses and share the same field of view and the same pixel resolution. The flow is seeded with 1 μm DEHS particles and illuminated by a light sheet from a dual-cavity InnoLas SpitLight 1000 laser. Two laser pulses with a temporal separation of 50 μs are emitted in synchronization to the camera timing. The two recorded frames are evaluated using a multi-grid cross-correlation analysis. For better comparability, no outlier detection is applied. In a dark environment (top diagrams) both cameras show a low noise level. In the presence of background light (bottom diagrams), however, the ‘double shutter’ camera exhibits an increased number of spurious velocity vectors while the noise level of the new fast shutter camera stays constant.
Despite the advantages of the FOX mode as demonstrated above, the apparent drawbacks have to be considered, too. First, the binning-like process not only reduces the number of total pixels, but also leads to a rectangular pixel shape with an aspect ratio of 2:1. In metrological applications the camera system is typically calibrated using precision targets such as calibration grids. With the results of this calibration the images are dewarped to cancel out any influence of camera lenses and image sensor properties. Thus no extra effort is necessary to address the pixel aspect ratio. However, with the pixel size doubled in one dimension the cross-correlation evaluation may become more susceptible to peak-locking (Westerweel 1997). Special care has to be taken in the layout of the imaging system to limit this effect. Second, the exposure time of the second frame differs for odd and even numbered pixel lines (compare Figure 2/3). With flash illumination, this is of no concern since only background illumination is affected and both exposure times are still
several orders of magnitude below the one achievable with the ‘double shutter’ technique. In contrast, with continuous illumination a bias in the object position can occur, which unfortunately cannot be avoided.

4. Conclusion

The new fast shutter mode ‘framing-optimized exposure’ (FOX) is presented. It can be integrated in suited standard PIV cameras without any restrictions to the normal operation. For the first time, two frames of short exposure time can be captured in fast succession with a high resolution image sensor. Both frames use the complete light sensitive area and are completely congruent, i.e. no line displacements or light insensitive lines exist. The presented results obtained with a prototype camera demonstrate the outstanding properties of this technique for metrological applications especially when used with flash illumination in bright environments. In double-frame applications, this new mode of operation can compete with – or even outperform – the latest single-chip high-speed image sensors available today. Using the optional third frame enables the implementation of advanced evaluation schemes for PIV (Lynch & Scarano 2013, Schröder et al 2013, Hain & Kähler 2007, Sciacchitano et al 2012) and particle tracking.

References