Spatial filtering technique for measurement of 2C flow velocity

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Abstract Velocity measurements techniques are essential for a tremendous number of applications. The number of velocity measurement techniques for flows also reflects the need in fluid mechanics. Especially optical methods as Laser Doppler or particle image velocimetry are advantageous, because they can be used in-situ without disturbing the fluid flow. Another optical method for determination of velocities is the spatial filtering technique. Although spatial filtering technique is widely spread for velocity determination of solid surfaces only a few applications in fluid flows exist. The present paper gives a short overview of the spatial filtering technique and presents two new developments, which are associated with measurements for two components of flow velocity.

Two concepts are presented in this paper, both using the spatial filtering technique. The first is the application of a specialized position sensor. The sensor chip has 256x256 pixel and sums up the pixel values in every row and column internally. This is an essential calculation step for spatial filtering. After a periodic weighting of the pixel rows and pixel columns the values are summed in every direction. So the procedure for getting a spatial filtering signal is very simple and on-line processing for frame rates up to 3200 Hz are feasible.

The second concept uses selected pixels of an image to detect blood flows in human capillaries. The challenge in practical use is the natural movement of the human finger. There is the need to follow one and the same capillary in the captured pictures. After detecting the capillary the calculation of the spatial filter signal starts. By using this strategy it becomes possible to determine the velocity of erythrocytes in human capillaries on-line with a temporal resolution of about 1kHz.

1. Introduction

The determination of velocity is essential for a wide range of applications. Also the increased number of measurement techniques for detection of flow velocities shows the need in fluid mechanics. Current optical measurement systems have the advantage to be in-situ contact-free and with high temporal and spatial resolution. Commercial available measurement systems for flows, like Laser-Doppler technique (Albrecht, Borys et al. 2003) or the Particle Image Velocimetry (Raffel, Willert et al. 1998) are mostly very expensive because of the optical components, light sources, detection systems and adapted signal processing hardware. Consequently, there is the need of simple but precise measurement systems. The spatial filtering technique determines the surface velocities using optical gratings and was invented in 1963 (Ator 1963). Since this first contribution, a number of systems for different applications were developed (Michel 2000; Bergeler 2002; Aizu and Asakura 2006). There are many applications to determine the velocity of surfaces by the spatial filtering technique but only a few applications in fluid flows. This article gives an overview of two innovative realizations using the spatial filtering technique for determination of two component flow velocities.
2. Principle of spatial filtering technique

The optical spatial filtering technique uses optical gratings in the receiver path. The image of a moving object e.g. particles is weighted by this grating. For 1C velocities the movement of the image in the sensor plane can be written as \( b(x, t) - x \). This image is multiplied by the grating function \( a(x) \). The output signal \( s(t) \) of the spatial filter results from the integration over the whole image

\[
s(t) = \int_{-\infty}^{+\infty} b(x, t) - x \, a(x) \, dx
\]  

(1)

By using CCD or CMOS sensors the aperture of the pixels can be used as a grating function. However the light sensitive area is limited by the size and number of pixels \( p \). So the integration becomes a sum of discrete pixel values:

\[
s(t) = \sum_{n=1}^{p} B(x, t - n) \, A(n)
\]  

(2)

whereas \( B(x, t - n) \) is the integrated signal over the area of pixel \( n \) regarding to the image intensity distribution and the pixels aperture. \( A(n) \) is the value of the discrete weighting function for the same pixel. The advantage of using CDD or CMOS sensors is the possibility to generate arbitrary grating functions \( a(x) \) by weighting the pixels with individual values. The sensor area becomes a virtual grating. A simple example of such a grating is a weighting of +1 and −1 as shown in figure 1, already for an array sensor. Because of the positive and negative weightings the output signal is mean free. Therefore the background intensity level of the moving structure is canceled out and the output signal of such a differential grating represents only velocity information. Other weighting functions like sinusoidal weightings are possible too.

![Figure 1: Generating of a virtual differential +1 / -1 grating with a structured receiver](image-url)
The output signal of the spatial filter is generated temporally and results in a periodic behavior. To determine the velocity of the moving image the peak frequency $f_0$ in the signal spectrum $S(f)$ has to be estimated. By using the lattice parameter of the grating $g$ and the sample rate this frequency can be directly converted to the velocity of the image:

$$f_0 = \frac{v_0}{g}.$$  

After the velocity of the object can be calculated by using the magnification $M$ of the imaging system:

$$v = \frac{v_0}{M} = \frac{f_0 g}{M}.$$  

The concept of the spatial filter can be extended to two component velocity measurements by using a second grating, which is rotated by 90 degree (Bergeler and Krambeer 2004; Aizu and Asakura 2006).

### 3. Application of an optical position sensor for spatial filtering

A problem of CCD and CMOS array sensors is the low frame rate already for moderate pixel numbers. A sensor with 256×256 pixels and a resolution of 8bit requires a bit rate of 0,5Gbit/s for a 1k frame rate. Therefore standard CCD and CMOS sensors can not been used for the spatial filtering technique in the kHz frame rate region and on-line processing.

To overcome this limitation an optical high speed profile sensor from Hamamatsu was implemented. This sensor has 256×256 pixels and sums the pixels values of each line and column internally. So the transfer rate is reduced from 256×256 values down to 2×256 values. The sensor is able to reach frame rates of 3200 frames/s at a resolution of 8 bit. Figure 2 shows the original functionality of the sensor to detect the position of a light spot with sub-pixel resolution.

![Figure 2: On-chip pre-processing of pixel values used for spatial filtering technique](image)

However, this on-chip pre-processing is required for the spatial filtering technique. After reading the rows and columns the values are periodical weighted and summed for each direction.

For testing the sensor a simple microcontroller interface was developed. The microcontroller reads
out the sensor data and sends the data via USB to a PC. First tests were made with a low frame rate and a high resolution. Figure 3 shows first measurement results for the small velocity of a surface.

![Figure 3: Measurement results for slow velocities](image)

One application example for such low velocities is a boundary layer measurement. Because the spatial filtering is very sensitive to focused images the technique can use the focal depth of the optical system to select the wall distance.

### 4. On-line processing of images for detecting blood flow in human capillaries

The principle of spatial filtering was also used for velocity determination of the erythrocytes in human capillaries of a finger (Bergeler, Krambeer et al. 2004). The frames were captured by a standard CMOS camera and transferred to the PC via an applicable frame grabber card. Figure 3 shows a complete frame from the camera. The image illustrates the capillaries and their dimensions at the nail fold. An area of interest was selected and grabbed to increase the frame rate. Frame rates between 750 and 1000 frames per second were reached with a size of 200x200 pixels for the area of interest. The spatial and temporal resolution was determined by the time scale of the blood flow and the necessary resolution of the small capillaries. Therefore 30 to 40 megabytes per second must be processed.

![Figure 4: Image of capillaries captured by the used camera](image)
To achieve the requirements of an on-line measurement, the process is subdivided in three signal and data processing parts. In a first step the capillary path is localized. This can be done by averaging the gray scale of successive images. The moving erythrocytes are canceled out by this step.

In practical use, the unavoidable finger movements of the patients inducing problems in the localization of the capillary. Therefore the second step determines the actual displacement of the capillary due to finger movement in relation to the reference location from the first step. This correction of the location is an important step, because the finger movement is also measured by the spatial filter and superimposed over the velocity of the erythrocytes. The correction requires a very fast and simple algorithm, because frame rate of up to 1000 frames/s should be processed on-line. Because feature tracking and correlation methods needs much computing power also the spatial filtering technique for the whole image were used (Menn, Wild et al. 2007). One example of the measured finger movement is shown in Fig. 5

After the detection of the movement the pixel positions of the capillary can be extracted for further processing. In the third signal processing step a spatial filter was constructed for this reduced number of pixels along the capillary way. According to the complex filter function of the spatial filter the selected pixels were weighted and subsequently summed. This results in one sample of the spatial filter signal for each frame. Because of the high frame rate and the resolution the instantaneous velocity of the imaged erythrocytes can be extracted from successive samples. This also needs additional signal filtering to eliminate disturbances. To obtain a velocity value the signal from the spatial filter is multiplied with the calibration constant of the optical system. As already described in section 2 this constant depends on geometric dimensions of the measurement systems, the grid period of the filter function, magnification of the optical lens and the frame rate of the camera. Nevertheless the system must be calibrated only time.

One measurements example of temporal resolved blood velocities along the path of the capillary is showed in figure 5.

\[ \text{Figure 5: Finger movements during the measurements of blood cells} \]

\[ \text{[Graph showing finger movements over time]} \]
5. Conclusion

The paper presented two concepts for determining the 2C flow velocity using spatial filtering technique. The first strategy uses a specialized position sensor which is well suited for detecting flow velocities. The second concept presented in this paper uses the spatial filtering technique in the first step for movement estimation of a whole frames and in the second step for calculating the velocity of erythrocytes along a path of a capillary inside the frames. Both solutions work with low cost standard components and have the potential precise velocity measurements in fluid flows.

6. References