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VELOCITY MEASUREMENTS IN CAPILLARIES

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Abstract: A new velocimeter for measurements in microscopic regions is presented. A common charge coupled device (CCD) has been used as spatial filter for one-component velocity measurements. The characteristics of this sensor are investigated and first application results presented.
Keywords: Charge coupled devices, optical velocity measurements, blood cell velocity

1 INTRODUCTION

Spatial filtering velocimetry (SFV) is a well-known optical technique for determining the velocity of moving objects based on the scattering of light on optical inhomogeneities [1, 2]. The most developed technology for SFV is based on the usage of a number of photodetectors. Schulz and Fiedler suggested to replace the separate receivers by a charge coupled device (CCD) [3]. Velocity sensors based on these solid-state imagers have been used for measurements on a variety of surfaces and inside a a circulating fluidized bed [4]. Several authors verified the usefulness of complicated spatial filtering systems based on transmission gratings or fiber arrays for the measurement of flow in glas tubes, capillaries and small vessels [5, 6]. In this paper the application range of CCD-sensors will also be extended to measurements in these microscopic applications. A new generation of highly miniaturized spatial filtering velocimeters particularly suited for the requirements in these applications will be presented. Furthermore, a novel CMOS sensor has been applied for measurements.

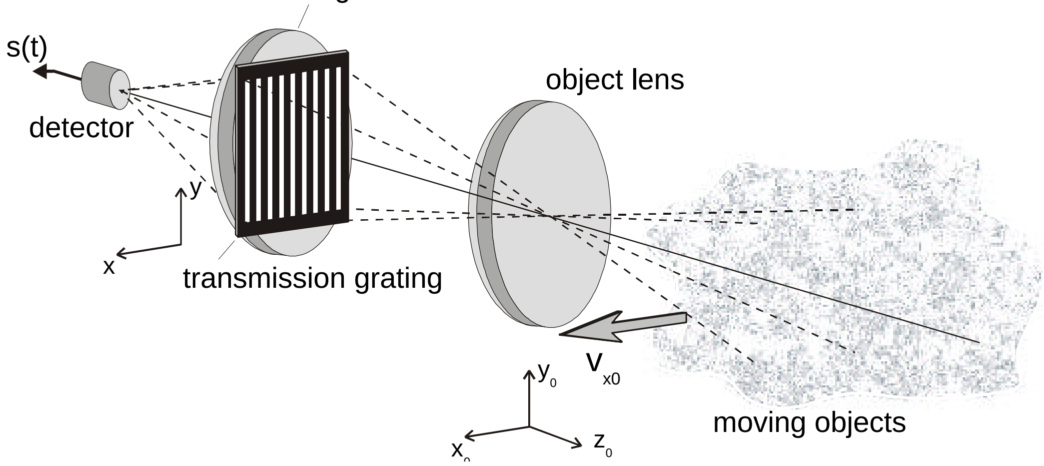

Figure 1. Principle of spatial filtering velocimetry

2 FUNDAMENTALS

The basic principle is shown in Figure 1. A photodetector observes moving objects throught a number of parallel slits. The output signal of the detector s(t) contains a frequency, which is proportional to the velocity of both particles or surfaces.

$$v = \frac{f \cdot g}{\beta} \tag{1}$$

where *b* denotes the optical magnification (image scale) and g the interval of grating lines. Instead of transmission gratings or optical fiber arrays in our approach photodetector arrays (such as CCD lines) are acting both as detectors and as the spatial filter. These sensors ensure the required high precision of the grating, and misalignment problems are drastically reduced. Detailed investigations of all sensor design aspects have been carried out in order to ensure optimal filtering characteristics of the sensor [2]. The sensor employs a differential grating arrangement in order to remove the dc component in the output signal without additional filtering. A realization of a differential grating is shown schematically in Fig. 2. Furthermore, depending on the pattern size of the measuring object different weighting functions can be realized by using different clocking regimes. This flexibility has significant practical advantages.

By arranging the detector readout in a way that two phase orthogonal gratings are formed, even the advantageous quadrature signal processing technique may be used for velocity estimation [7, 8].

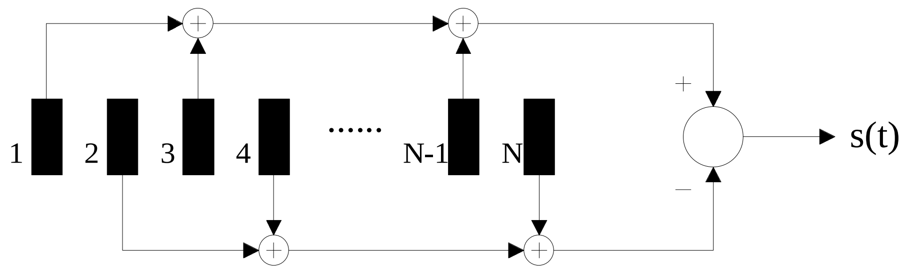

Figure 2. Schematic of a differential grating spatial filter using a line sensor

3 SIGNAL PROCESSING

Several signal processing techniques can be used in order to determine the central frequency of the spatial filter output signal. Commonly used are the fast Fourier transform [6], the counter principle [2] and the quadrature demodulation technique [5].

A typical output signal recorded at a velocity of about 11,4 mm·s^{-1} is shown in Fig. 3(a). The output signal has been processed in a PC using a LabView based software. The frequency f related to the velocity of the particles in the liquid is estimated using a fast Fourier transform algorithm. Fig. 3(b) shows the spectrum of the output signal.

4 EXPERIMENTAL RESULTS

The new sensor already proved to be useful for measurements of the flow velocity in small cylindrical glas tubes. The flow velocity distribution in such a tube (280 µm diameter) has been measured in order to investigate the spatial and temporal resolution of the sensor. Fig. 4 shows the experimental setup. A beam splitter is included in order to observe the image while the object velocity is being measured. Both a CCD line sensor and a CMOS-Camera (512 x 512) with direct pixel access hve been used for the actual measurement. In however, in practice only a line of 256 pixels corresponding to 8 grating periods has be

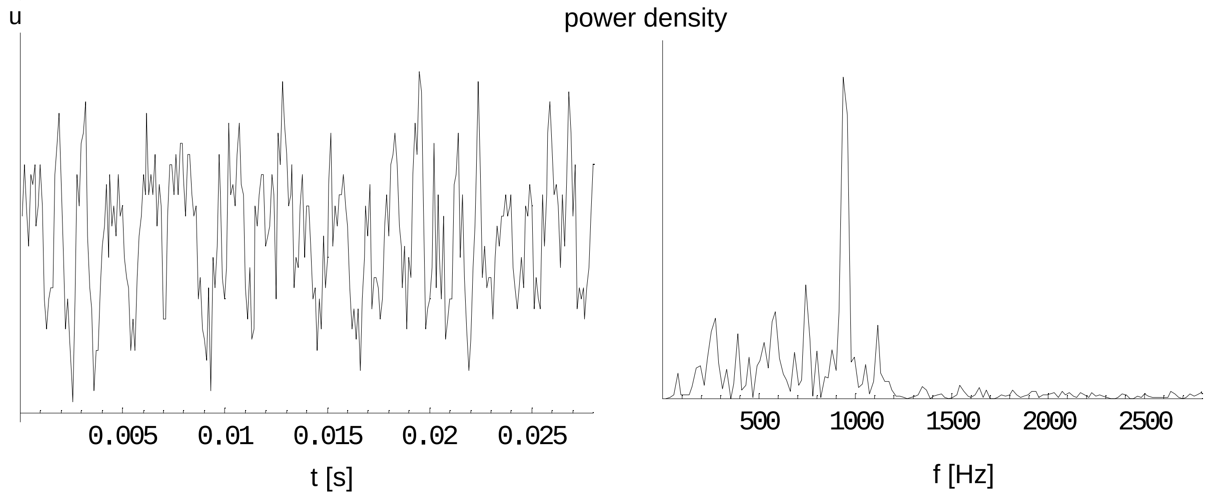

Figure 3. Output signal (a) and its power density spectrum (b)

Many lenses can be adapted for online microscopy, for instance microscope objectives, enlarger lenses, camera lenses or custom lenses. Finally, a Tevidon 1,4/25 camera lens which works „backward“ has been chosen. This inexpensive solution provides a total magnification in this optical path of about 12,28x, a working distance of 17 mm and a depth of field of 5 µm.

The experiment was performed using a liquid with the optical properties of human blood (particle sizes of 5...10µm correspond to the size of the red blood cells. However, this liquid did *not* match the non-Newtonian behaviour of human blood. With a viscosity of 697 mPa/s and a resulting Reynolds number of approximately 0,01 the flow is laminar. Therefore, the theoretical velocity profile could be calculated using

$$v(r) = v_{max}\left[1-\left(\frac{r}{R}\right)^2\right] \tag{2}$$

with v_{max} being determined from the flow rate known from the pump.

Fig. 5 shows the velocity distributions and their standard deviations compared with the theoretical values.

Currently, the sensor is used in order to perform *in vivo* measurements of the blood cell velocity in capillaries at the human nailfold. The fingernailfold is extensively used for analysing morphological changes of skin capillaries in different systemic diseases [9]. The sensor represents a cost-effective alternative to transmission gratings, frame-to-frame analysis and laser Doppler velocimeters [9] currently used for the investigation of human microcirculation.

In this application the observation camera, a standard CCD-Matrix-Camera (768 x 576 pixels), is used in order to get an overview of all the nailfold capillaries at a total magnification of 5x (Fig. 6). In these capillaries velocities from almost zero up to only 2 mm/s can be expected. In order to avoid the problems usually associated with velocity components near or equal to zero carrier modulation techniques may be used in order tor ealize a frequency shift of the output signal.

The illumination is a crucial parameter in this application. This measuring system uses a ring illumination with green LED´s in order to achieve a high contrast between the red blood cells and the surrounding tissue. Another problem is the detection of particular capillaries. The use of two cameras enables the selection of a particular capillary for the measurement.

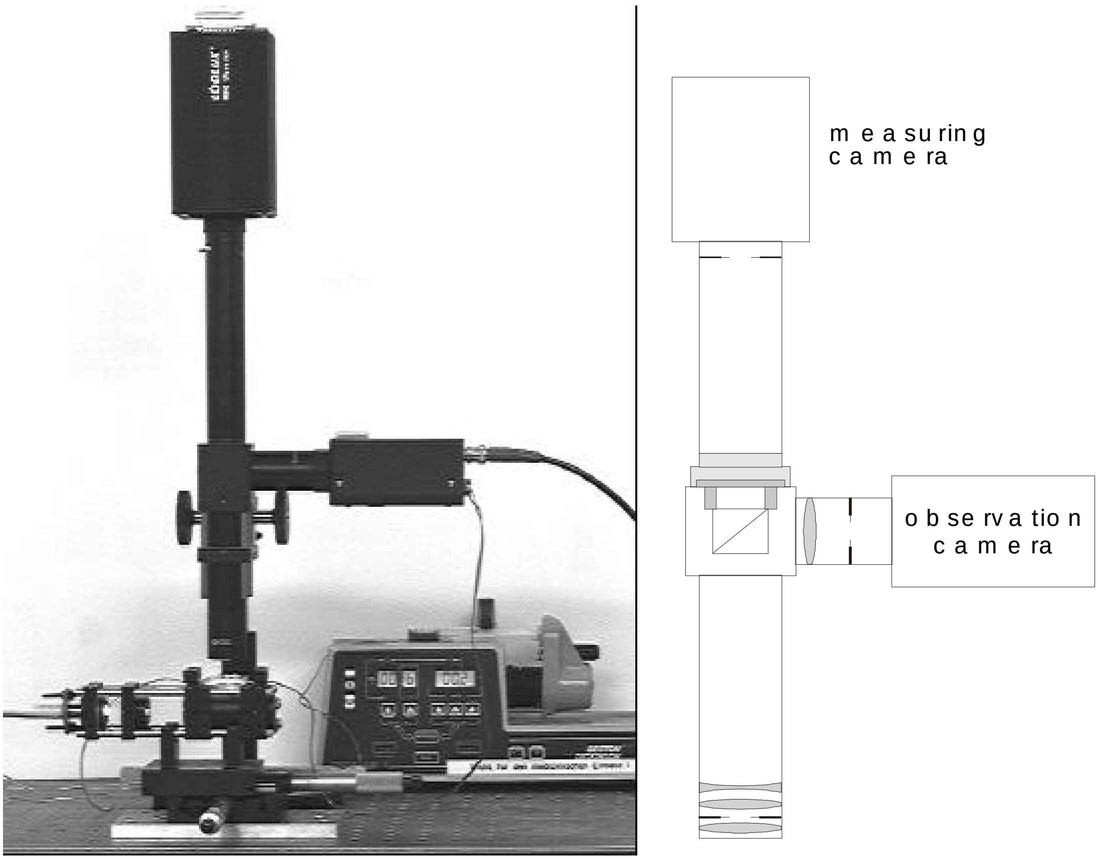

Figure 4. Experimental setup

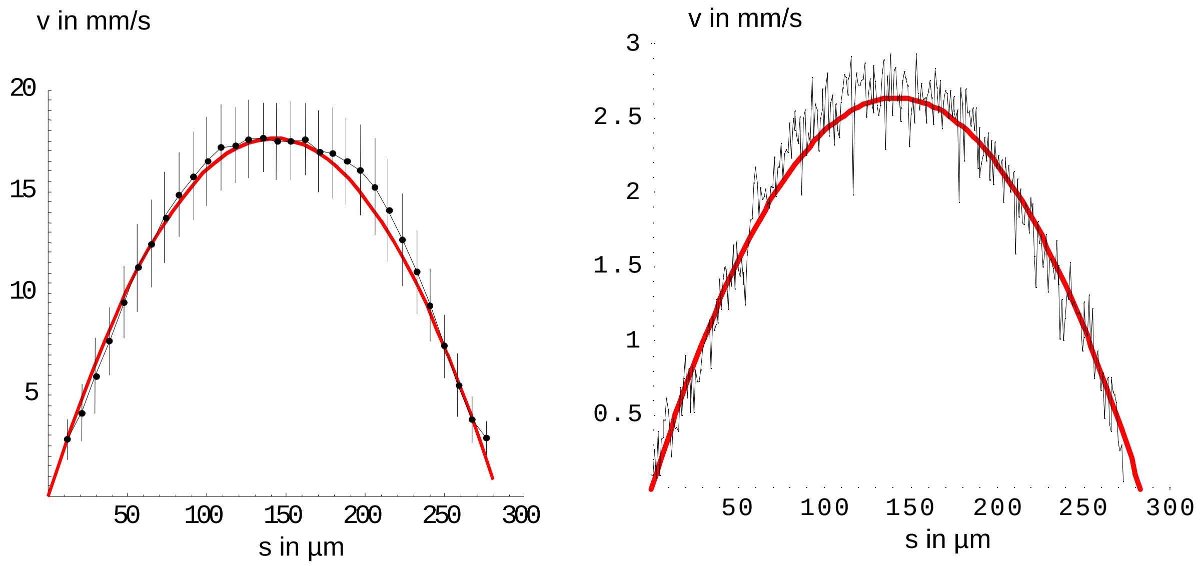

Figure 5. Velocity profile and theoretical values (thick lines) for a liquid with the optical properties of human blood, recorded with a CCD line sensor (left) and a CMOS camera (right)

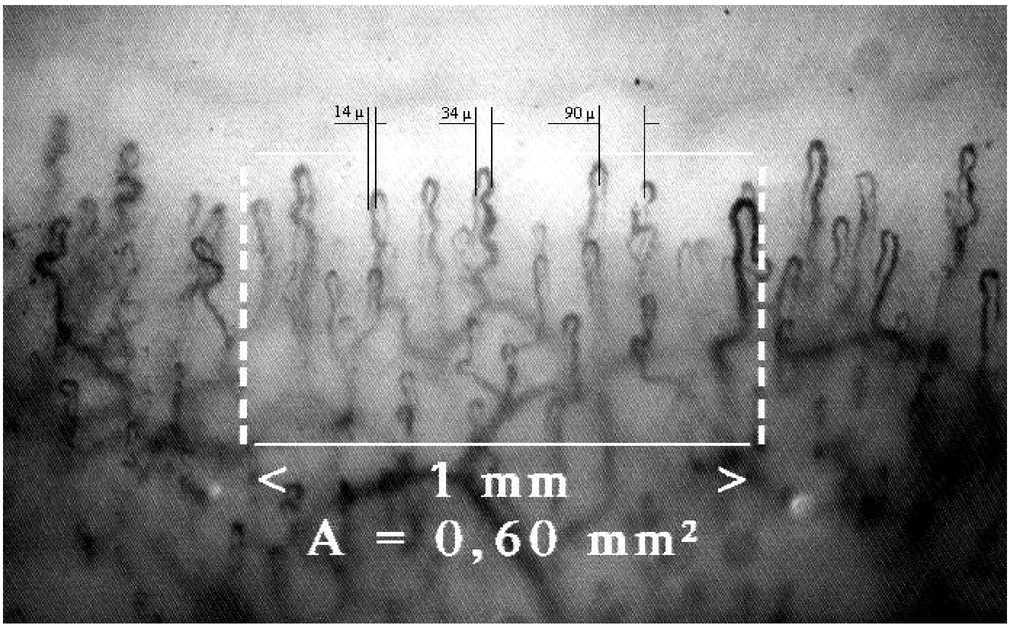

Figure 6. Typical image of normal fingernail-fold capillaries

5 CONCLUSIONS

A novel velocimeter for measurements in microscopic applications incorporating either a CCD line or a CMOS sensor has been presented. The design of the instrument and first experiences have been discussed. The new sensor appears to be a valuable and cost-effective tool for the investigation of microcirculation.

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