Laser Doppler Velocimetry

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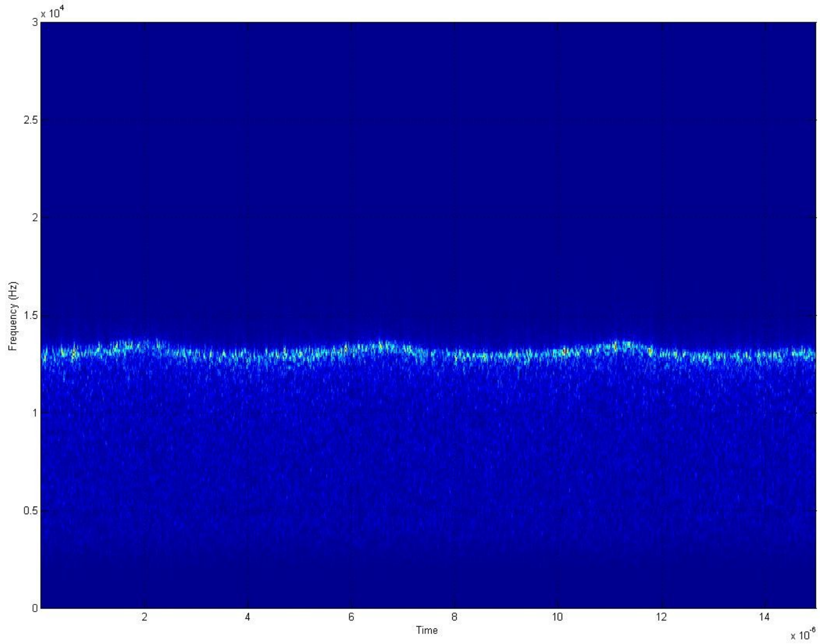

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1 Introduction

In many physical experiments it is necessary to measure flow velocities in the experiment without disturbing the natural flow patterns. A very useful method to accomplish this task is the laser Doppler velocimetry (LDV). LDV is used in the study of various flows like atmospheric turbulences and flows in internal combustion engines. Its noninvasive nature makes it especially interesting for medical and biophysical applications where it is of great interest to measure the flow of blood in localized areas. The motivation of this project was to set up a laser Doppler velocimeter and study the characteristics of different flow patterns to evaluate the potential of this method.

2 Laser Doppler Velocimetry

2.1 Theory

The experiment uses the Doppler effect to calculate the velocity of particles in fluids. Light scattered on moving particles experiences a shift in frequencies according to

$$f_r = f_b \frac{1 - \frac{\vec{e_b} \cdot \vec{v_p}}{c}}{1 - \frac{\vec{e_{pr}} \cdot \vec{v_p}}{c}} \approx f_b + \frac{\vec{v_p}}{\lambda_b} \cdot (\vec{e_{pr}} - \vec{e_b}) \quad (1)$$

where f_b and f_r are the frequencies of the beam and the light at the receiver. $\vec{v_p}$ is the velocity of the particle and $\vec{e_b}$ is the unit vector in beam direction. $\vec{e_{pr}}$ is the unit vector pointing from the particle to the receiver. λ_b is the wavelength of the beam. To derive the second formula we used the approximation $|\vec{v_p}| << c$. Notice that the light is shifted twice. Once at absorption and once at emission. Since this shift is too small to be measured directly, we use the principle of optical beating. For this we need two beams, coming in at an angle θ between the beams, which are both

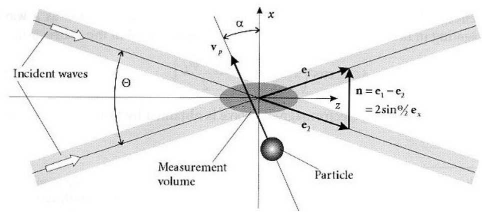

Figure 1: Dual-beam configuration

scattered off the particles. The two beams are then heterodyned on the detector to obtain an optical beating frequency in a range which can be measured. Using the formula above and some geometrical arguments (see Figure 1) we obtain

$$f_d = f_2 - f_1 = \frac{2 \cdot \sin(\frac{\theta}{2})}{\lambda_b} \cdot |v_{pt}| \quad (2)$$

As one can see, f_d is completely independent from the position of the receiver. This is a huge advantage concerning the setup of the experiment. However, only the velocity component which lies in the plane defined by the two laser beams and perpendicular to the optical axis can be obtained. But this is only of minor importance for one-dimensional laminar flow patterns as for example in a tube or a blood vessel. A more intuitive explanation of this formula using fringe patterns can be found in the literature [1, 2, 4]. Although this path of explanation helps to understand the origin of the signal in a very nice way, it can not explain all observed phenomena [3].

2.2 The Experiment

2.2.1 Experimental Setup

Our setup is shown in figure 2 on the next page. In this setup a 2 mW He-Ne laser was used. The laser beam is then divided via a cube beamsplitter and a right-angle prism is used to obtain two parallel beams. These two beams are then sent through the emitting lens and meet at it's focus to form the measurement volume. Due to the gaussian nature of the laser beam the measurement volume has an elliptic form. The test solution, 1μm micro beats suspended in distilled water, flows through a transparent tube placed around the measurement volume. The flow is driven by a height difference of the water level in the container with the test solution and the end of the flow tube. This method also enables us to easily change flow velocities. If a particle crosses the measurement volume it scatters light of both beams into an objective. Since the laser beams intersect with an angel of $\Theta = 13°$ we had to move in our objective (which is normally collecting from a 15° angle) to prevent the laser beams from entering the receiving optics. Therefore a second lens was placed behind the objective to focus the scattered light on the photo diode. To increase the spacial resolution a spacial filter with a pinhole was set up in front of the photo diode. Unfortunately our signal intensity was to weak to actually use the pinhole. To be independent of environment light a 632.8 nm laser line filter was placed in front of the photo diode.

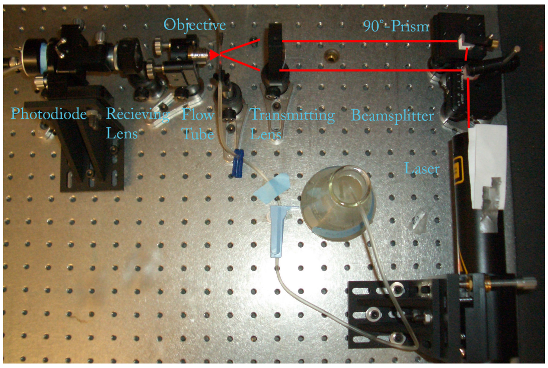

Figure 2: Experimental setup

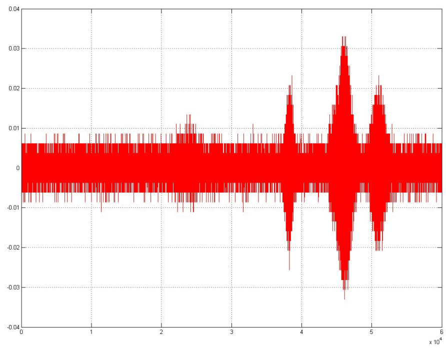

Figure 3: Signal in time domain

2.2.2 Data Processing

The signal from the photo diode is fed into a current amplifier and amplified by a factor of 10^4. To get a better signal to noise ratio the current amplifier is followed by a band pass. The range of the bandpass can be adapted to the current experimental configurations. For instant monitoring we use an oscilloscope. An A/D-card is used to digitize the signal and make it available for further digital processing (see Methods). To transfer the signal into frequency space we used fast fourier transformation. It also turned out to be quite useful to look at the spectrogram of the signal.

3 Results

3.1 Small Flow Tube

The small flow tube that was used here was a 2 mm × 0.2 mm flat cuvette. With the described setup we measured the light intensity as a function of time. In figure 3 one can see particles passing through the flow tube at different times. Each particle shifts the laser light as described above. To calculate the velocity of the particles one needs the beating frequency caused by the shifted laser light. A typical measurement result of

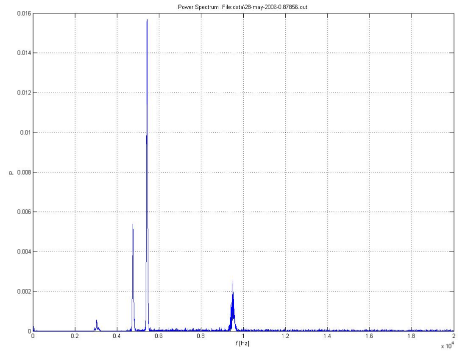

Figure 4: Signal in frequency domain

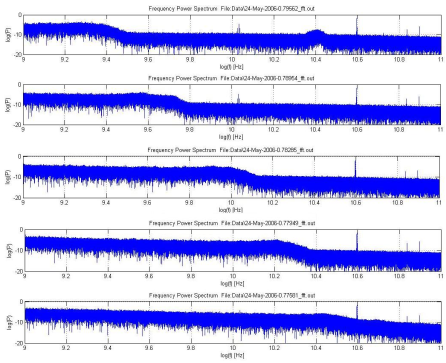

Figure 5: log-log plot of frequency-power-spectrum with different flow velocities

this can be found in figure 4. In the plot one can see the corresponding frequencies to several particles passing through as seen in the time domain. To check the velocity dependence of the setup and analyze the data further we took measurements at different height levels of the fluid. In figure 5 the height difference was changed throughout the measurements from top to bottom, with the biggest difference corresponding to the highest velocity at the bottom and the smallest height difference at the top of the graphic. One can clearly see the velocity dependence of the cutoff. With the help of formula 2 on page 3 one can calculate the

h[mm]	f[kHz]	v[cm/s]
24	11	1.5
30	14	2.0
38	20	2.8
44	27	3.8
54	34	4.8

Table 1: Relation of height difference, measured frequency and calculated particle velocity

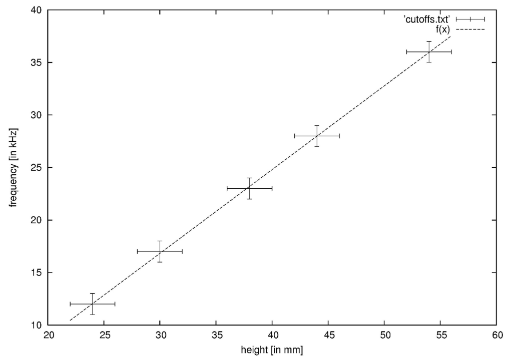

Figure 6: Height difference plotted vs. cutoff frequencies

particles from the frequencies. The conversion of the described measurement can be found in table 1. To get the height dependence of the cutoff frequency see figure 6, where the cutoff frequency is plotted against the height. We fitted this graph with the help of gnuplot and found a linear dependence.

3.2 Big Flow Tube

But why exactly is there a cutoff in the graphic and not as expected a maximum? Why is there a maximum frequency and a plateau at lower frequencies? To answer this question, we experimented with different concentrations of particles in our fluid and finally with a bigger flow tube. Taking a look at picture 7 on the follow-

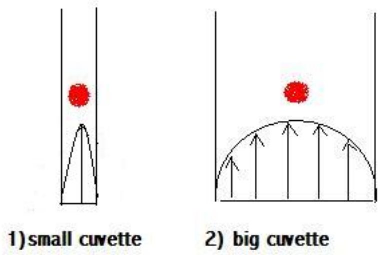

Figure 7: Comparision of the velocity distribution in a small and bigger cuvette

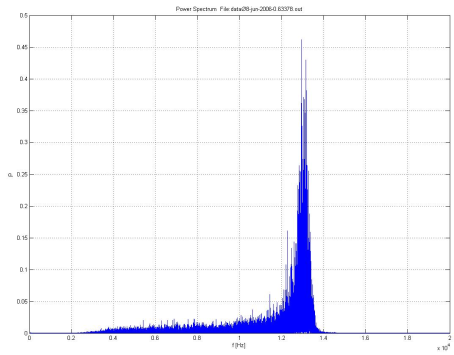

Figure 8: Frequency-power-spectrum with the bigger cuvette

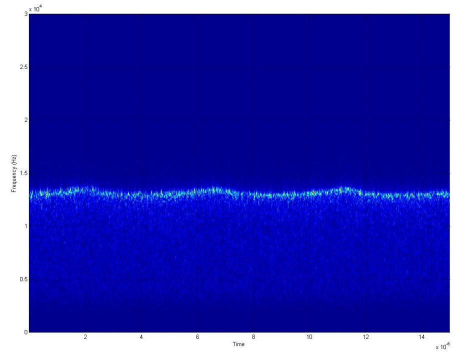

Figure 9: Spectrogram of the signal

ing page one can see the wider distribution of velocities in the smaller flow tube in the same size of measurement volume (represented by the red dot in the pictures). This explains the wide range of frequencies in the first measurements. The cutoff is due to the fact that there is an upper limit on particle velocieties. The frequencies at the cutoff frequency correspond to the fastest particles moving through the measurement volume, the lower frequencies to the slower particles. We therefor exchanged the $0.2 \times 2\ \mathrm{mm}^2$ flow tube with a circular flow tube with a diameter of 6 mm. The measurement result with the new flow tube can be seen in the spectrum in figure 8. In this plot one can see the anticipated maximum at 13 kHz, and not as before a cutoff. This relates to a much more narrow velocity distribution in the measurement volume. To analyze the data further we looked at the spectrogram of the signal. The time is plotted on the x-axis, the frequency on the y-axis and the color is proportional to the Power. This was done in picture 9. One can see a periodical change in frequencies over time. This corresponds to the water drops falling off the end of our flow tube, which change the velocities and therefor the frequencies. The oscillatory nature of the signal had to be considered in the evaluation. Still, it was very nice to observe this kind of signature. Changing the height of the water levels (and therefor the velocities) changed the frequencies as seen in figure 10 on the following page. A plot of the peak-frequency versus the height differences of the water levels gave again a linear dependence (see the gnuplot graph 11 on the next page). But why is there still a tail at lower frequencies. This tail probably corresponds to multiple scattering of particles in the measurement volume [3]. To

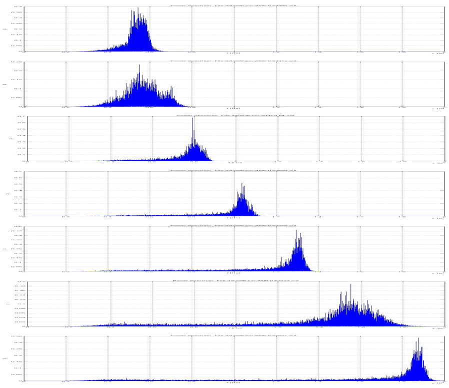

Figure 10: Frequency-power-Spectra of different flow velocities in the bigger flow tube

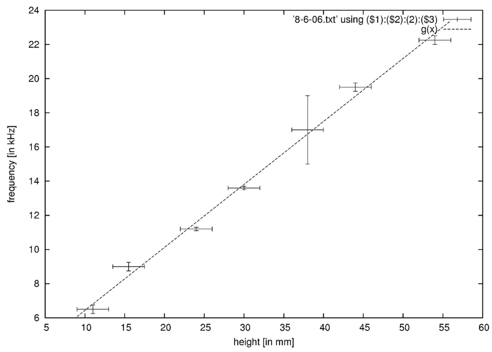

Figure 11: height difference plotted vs. peak frequencies

check this assumption we reduced the concentration of particles in our fluid. The results showed a dramatically bigger signal to tail ratio in the case of lower concentrations. This supports the hypothesis since a lower concentration of particles decreases the relative probability of multiple scattering.

4 Discussion

The outcome of the experiment exceeded our expectations. In case of the small flow tube, where we found a wide distribution of velocities in the measurement volume, the flow characteristics can be well described by the frequency of the cutoff. Isolating a single event in time space allows for a very exact measurement of the particle velocity. Taking a bigger flow tube narrows the velocity variations in the measurement volume. This clearly reflects in the measured data which show a narrow maximum in the frequency-power-spectrum. Both variations allowed for evaluation of particle velocities but also gave insight to other flow characteristics. Looking closer at the relative contribution of multiple scattering might be a way to determine particle densities. It could be possible that the observed sudden broadening of the peak in the spectrum is connected to nonlaminar flow. The most important thing to gain more confidence in the results would be to create an alternative and sufficiently accurate method to measure the particle veloities and compare it with the LDV results. Our attempt to do this by observing the transported fluid volume was unsatisfactory. The already good results obtained with this basic setup motivate further improvement. Adding a collimator, for example, would enhance the spacial resolution by creating a smaller measurement volume. Using a more powerful laser would eventually make the signal strong enough to employ a pinhole and therefore increase the resolution of the receiving optics. The receiving optics could also be enhanced by choosing a more adequate objective. Reconfiguring the setup for back-scattering would make it possible to use LDV in a broader range of applications. It's noninvasive nature and the high time and (potentially) spacial resolution combined with a high level of versatility makes LDV an interesting method that should be kept in mind.

5 Methods

In order to have a flexible and efficient way to look at the acquired data we combined different data processing methods of matlab into one tool. This tool was of great assistance and will be described here. We also supply the matlab code for further insight (see appendix A). Although our primary interest was in the frequency distribution of the measured signal, there was more to consider in order to get a good evaluation in frequency space. Due to the random distribution of micro beads in the solution the number of events in a measurement can be unevenly distributed over the measured time period. Therefore it was necessary to select the essential parts of the time series before processing them further. This also enabled us to better understand velocity variations between different events. Another powerful method to look at the time dependence of the signal in frequency space is the spectrogram function of matlab. Running the `closelook(filename)` (where filename is the path of the file with the aquired data) function will open four windows. The first window (lower left) will show the spectrogram of the measured signal. Above it the entire time series is presented. Using the loop tool, a part of the time series can be selected for fft-processing. This part is then highlighted and shown magnified in the third window (upper right). Finally the Fourier transformation of the selected part of the signal is then shown in the fourth window (lower right). The selection can repeatedly be changed as described above as long as all windows remain open. Closing the selection window will terminate the function.

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