



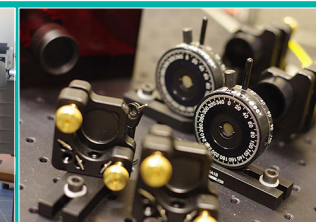
DLF

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Experiment 11

Determination of a particle's velocity using laser anemometry

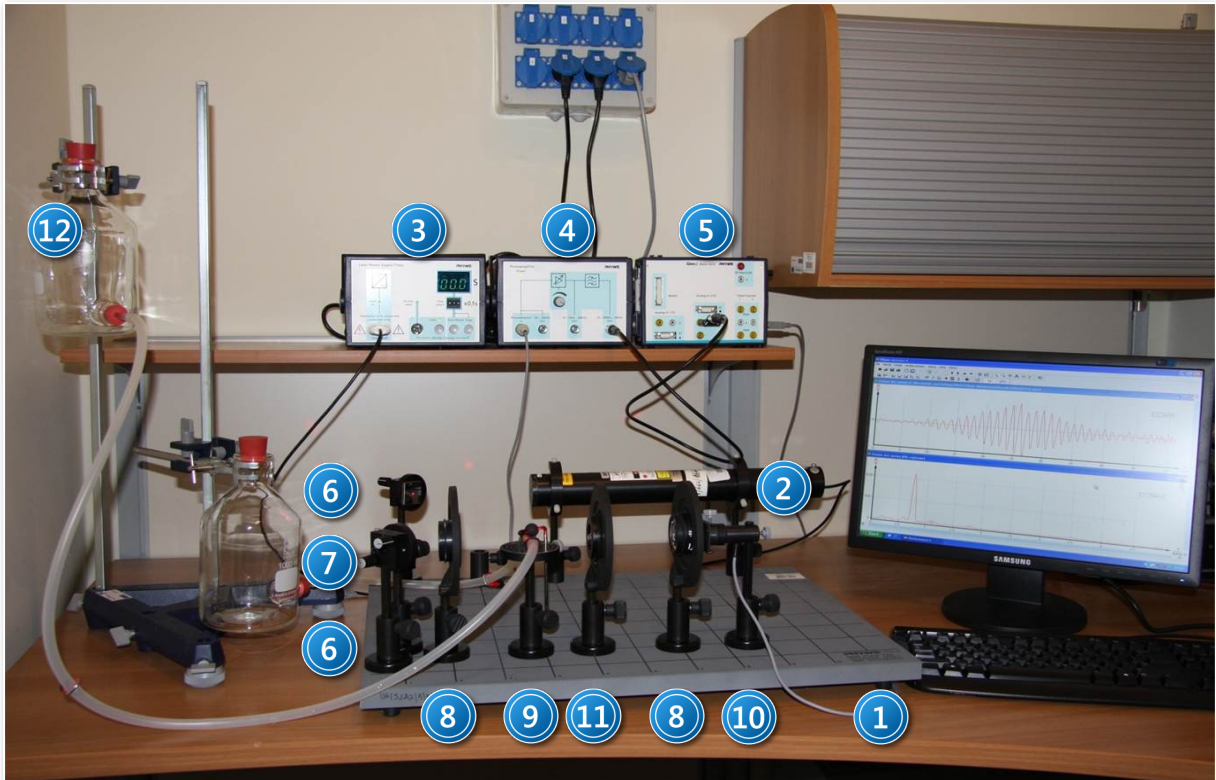


I. Background theory.

1. Laser doppler anemometry LDA (Doppler model):
 - a) LDA principles;
 - b) single and multi-channel LDA systems;
 - c) applications of LDA, advantages and disadvantages.
2. Electromagnetic waves.
3. Phenomena associated with the wave nature of light:
 - a) diffraction;
 - b) interference;
 - c) beats;
 - d) moiré patterns;
 - e) Doppler effect.
4. Scattering of light by particles (Mie scattering).
5. Fluid mechanics:
 - a) laminar and turbulent flow;
 - b) Reynolds number.
6. Signal processing and analysis:
 - a) spectral analysis of signals:
 - Fourier transform;
 - discrete Fourier transform;
 - spectral power density;
 - fast Fourier transform (FFT).
 - b) digital-analogue processing:
 - sampling;
 - Nyquist–Shannon sampling theorem;
 - aliasing (masking);
 - high and low-pass filters;
 - signal conditioning.
7. Beam path through a system of lenses and mirrors.
8. Construction and operation of He-Ne lasers.

II. Experimental tasks.

1. Refer to the experimental set-up in *Picture 1*.



Picture 1. Experimental set-up for the analysis of laser Doppler anemometry: 1 - base plate; 2 - He-Ne laser; 3 - laser power supply with controller; 4 - photodetector amplifier; 5 - Cobra 3 interface; 6 - plane mirror; 7 - beam splitter; 8 - lenses; 9 - mounted cuvette; 10 - photodetector; 11 - iris diaphragm; 12 - bottle (1000 ml).

2. Turn on the laser and the Cobra 3 interface (3 and 5 in *Picture 1*).
3. Start the "Measure" program and select "Miernik-Cobra 3 Analiza częstotliwości" from the menu.
4. Assemble the measuring system as described in part I of *Appendix A*.
5. Focus the interference pattern.
6. Take measurements of the distances described in *Figure 2* in part I of *Appendix A*.
7. Prepare a solution of micro-particles as described in part III of *Appendix A*.
8. Set up the experiment as described in part II of *Appendix A*.
9. Following the instructions in *Appendix B*, record an interference signal as a function of time and perform a Fourier analysis.
10. Based on the results obtained in part I of *Appendix A* and Formula (9) of *Appendix C*, calculate the half-angle φ (the angle between the beams, *Figure 2* in *Appendix A*).
11. Calculate the velocity of the micro-particles using Formula (8) in *Appendix C*.
12. Increase the flow-rate and repeat steps 9 – 11.

III. Apparatus.

1. Base plate.
2. He-Ne laser, $\lambda=632.8$ nm, 5 mW.
3. Laser power supply and controller.
4. Photodetector amplifier.
5. *Cobra 3* interface.
6. Two plane mirrors.
7. 50:50 Beam splitter.
8. Lenses with focal lengths : 20 mm, 50 mm, 100 mm.
9. Mounted cuvette.
10. Photodetector.
11. Iris diaphragm, circular aperture of $30\mu\text{m}$.
12. Two 1000 ml bottles.
13. Screen.

IV. Literature.

1. L.E. Drain – “*The Laser Doppler Technique*”, John Wiley and Sons, 1980.
2. F. Durst, M. Zare – “*Laser Doppler Measurements in Two-Phase Flows*”, LDA-Symposium, Copenhagen, 1975, p. 403-429.
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4. J. F. Douglas – “*Fluid Mechanics*”, Harlow, Longman, 1996.
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6. P.W. Milonni, J.H. Eberly – “*Lasers*”, John Wiley and Sons, 1988.
7. G.F. Lothion – “*Optics and its Uses*”, VNR, 1975.
8. M. Tadeusiewicz – “*Signals and Systems*”, Technical University of Łódź, 2004.
9. A. Reimann – “*Physics*”, Part 1 & 2, Barnes and Noble, 1971.
10. Sears and Zemansky's – “*University Physics with Modern Physics*”, Pearson Addison - Wesley, 2008.

Appendix A

Preliminaries

I. Obtaining an interference signal.

a) Using *Picture 2* and the diagram in *Figure 3*, set up the system components on the base plate, remembering that the coordinates are a guide for course adjustments only (aided by the grid on the base plate). Coordinates for the various circuit elements are given in square-brackets.

- Mirror M1 = [1,8]
- Beam splitter BS = [1,2.5]
- Mirror M2 = [1,1.5]
- Lens L1 with focal length $f=+100$ mm =[2,2]
- Screen S = [11,2].

The distance between the beam splitter BS and mirror M2 should not exceed 3 cm.

The beam splitter BS should be placed on the silvered side of the mirror M1.

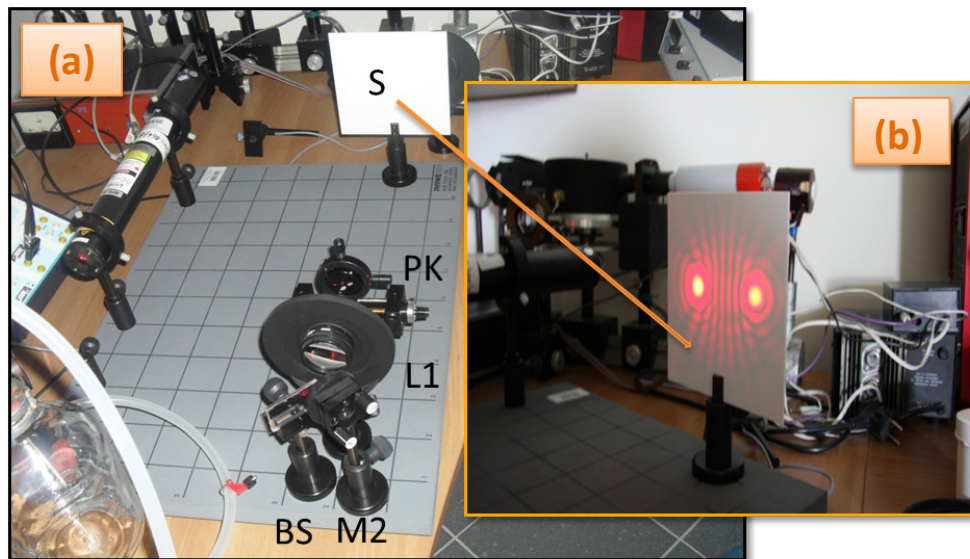
The recommended height of the beam above the base plate is 13 cm.

The parallel beams from the beam splitter BS and mirror M2 should be aimed symmetrically about the centre of lens L1. Two red spots will appear on the screen S.

Place the 30 μm iris diaphragm PK at position [4,2], at the point of intersection of the beams (10 cm from lens L1).

Adjust the positions of mirror M2, iris diaphragm PK, and optionally the beam splitter BS and lens L1 to create an interference pattern with the two beams.

After reflection by mirror M2, the beam's spot on the screen S should appear to the left, while the spot from the beam through the beam splitter BS should appear on the right (*Picture 2b*).



Picture 2. a) Circuit geometry resulting in interference of light beams; b) view of the image on the screen showing an interference pattern.



Hint

Adjustment of the height and direction of the two beams coming from mirror M2 and beam splitter BS will help to obtain an interference image.

To do this, set the lens L2 with focal length $f=+20$ mm at position [4.5,2], rotate the screen 45° (as shown in Fig.1) and check that the two beams are at the same height by adjusting the screws in the mirror M2. Then remove lens L2 from the optical path and get an interference pattern (the aperture PK remains at position [4,2], but may be temporarily removed during adjustments).

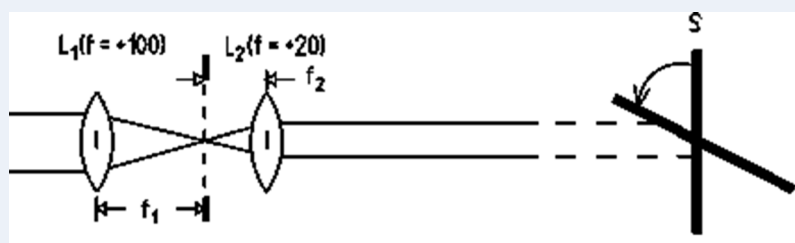


Figure 1. Diagram of set-up to ensure correct high and direction of beams (Phywe): L1, L2 - lenses with focal lengths $f = +100$ mm and $f = +20$ mm; S - screen.

- b) After obtaining a clear interference pattern, remove the aperture PK and measure the distances l' and D (Figure 2).

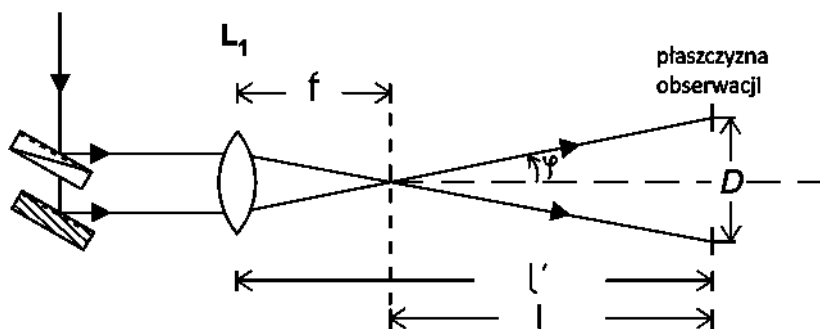


Figure 2. Schematic setup to determine the angle φ : l' - distance from lens $L1$ to the plane of observation; D - distance between the two spots of light on the plane of observation (Phywe).

II. Setting up the apparatus to determine micro-particle velocities.

Remove the screen S from the base plate.

Replace the aperture PK by the cuvette T = [4,2], ensuring that the light beams intersect at its centre.



ATTENTION!

The cuvette is very fragile, handle it with care.

With the help of Figure 3 and Picture 3, correctly position the following elements, whose coordinates are given enclosed in square brackets:

- Iris diaphragm PI = [5,2] (to restrict the area of observation to the Moiré rings);
- Lens L2 with focal length $f = +50 \text{ mm} = [7,2]$;
- Photodetector PD = [8,2].

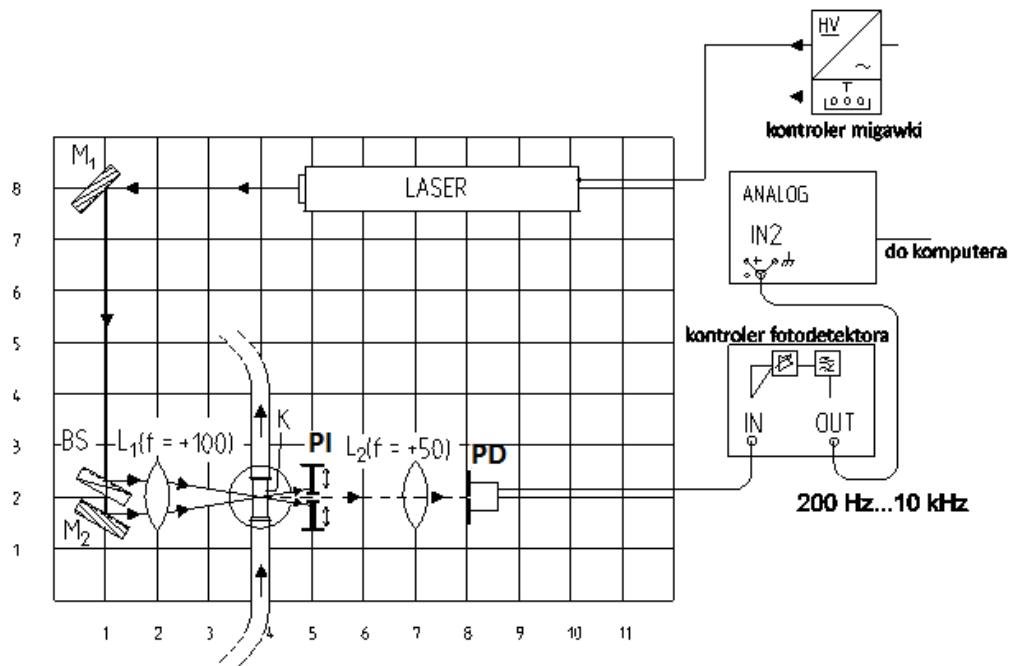
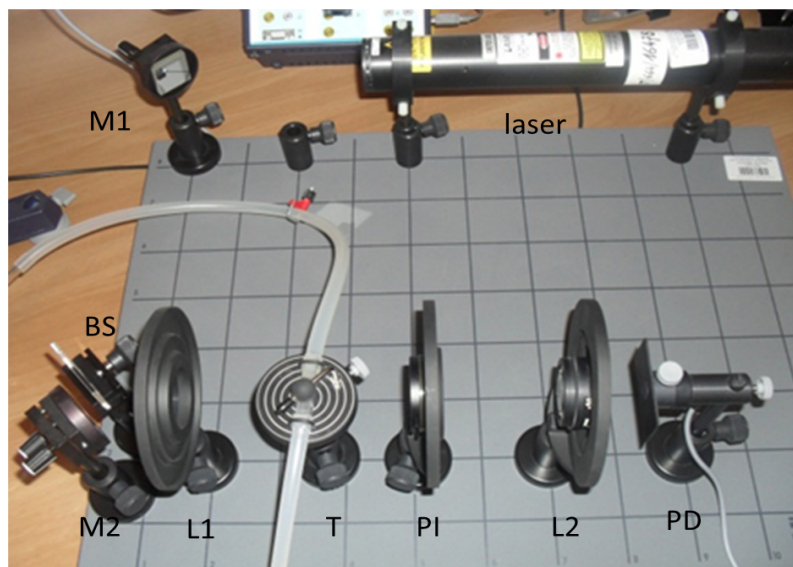


Figure 3. Schematic setup for determining the velocity of microparticles (Phywe).



Picture 3. System geometry allowing the determination of instantaneous flow rate.

III. Preparing the solution.

Add one drop of a suspension of micro-particles to be studied (silvercoat hollow glass spheres - meandiameter 10 μm in water) to 10 ml distilled water and mix 1-2 ml of the solution with 500 ml distilled water.

It is necessary to add a few drops of formaldehyde to the prepared solution to inhibit the growth of bacteria.

Mount a bottle of the prepared solution on a tripod. Mount a second empty bottle below the bottle with solution (*Picture 1*).

Adjust the clamps on the rubber hoses **very slowly** to establish a flow of liquid.

Appendix B

Recording a signal

Choose "Rejestracja pomiaru" from the menu.

Establish the voltage and frequency measurement. Start with small values (e.g.: $U = 0.3$ V; $f = 10$ kHz).

Select the options "Bez Wyzwalacza" and "Pomiar ciągły".

Click the button "Pomiar".

After obtaining a good signal, click "Zachowaj".

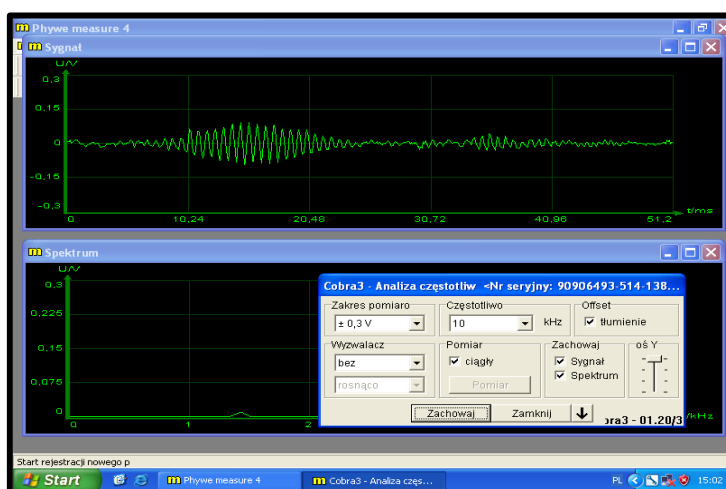


Figure 4. View of the program to measure flow velocity.

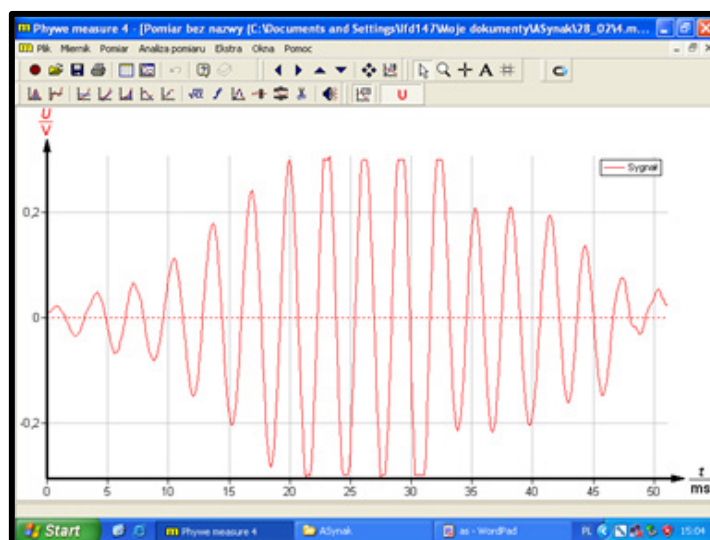


Figure 5. Interference signal as a function of time.

Make a Fourier analysis of the spectrum and calculate the peak frequency. The tool “Pokaż ekstrema” allows an accurate reading of the frequency.

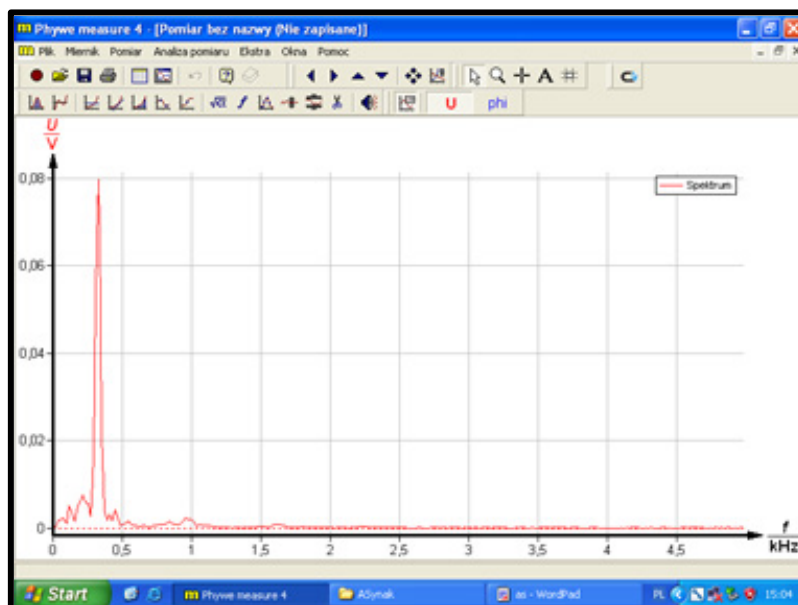


Figure 6. Fourier transform of the measured interference signal.



ATTENTION!

After 30 minutes, stir the solution to avoid sedimentation.

Do not lean on the table during measurements.

In the case of a weak signal, Fourier analysis can only be performed on the interesting part of the spectrum.

To do this, select “Zmierz”, select the desired range, and then choose “Analiza Fouriera”.

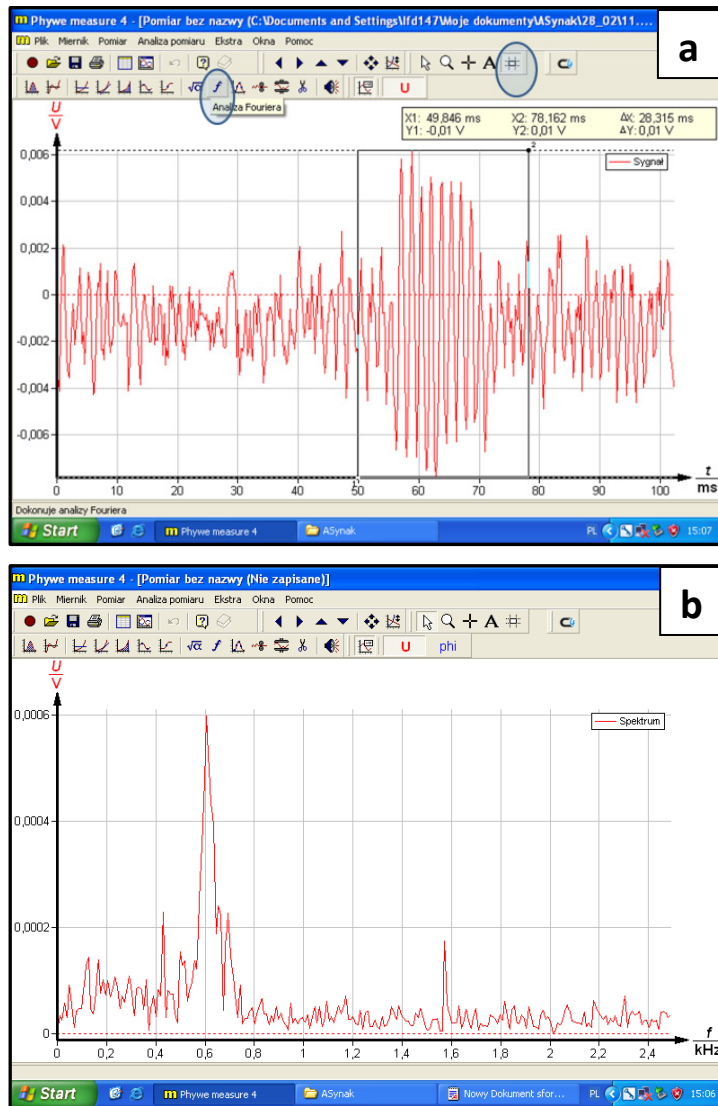


Figure 7. a) Example of analysis of a weak signal; b) Peak frequencies obtained by the Fourier transform of the signal.

In order to improve the signal, the positions of lens L2 with focal length $f = +50$ mm and the photodetector PD can be gently adjusted.



Hint

At low flow rates, it is possible to shift the maximum frequency of the measured signal too close to zero. In this case, you may have a problem determining the value of the measured frequency in the frequency domain (you should make measurements for different outputs on the photodetector controller - Picture 1, element 4).

Appendix C

Laser anemometry – fundamentals

Laser anemometry allows for measuring the speed of moving particles (elements) by scattered light [1]. Anemometry is based on two physical phenomena.

These are, the Doppler effect (A) and interference (B).

(A)

The Doppler effect is the change in frequency due to relative movement between the wave source and the observer.

Two cases of the Doppler effect have been used to discuss the principles of LDA (Figure 8).

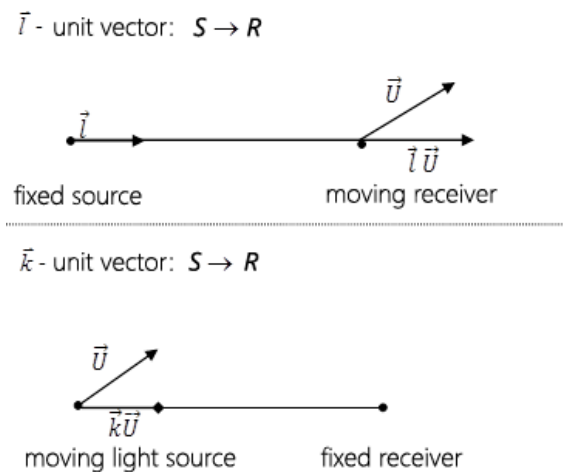


Figure 8. Two cases of the Doppler effect.

- a) In the first case, the source is stationary and the observer is moving, with a velocity of \vec{U} . The frequency observed by the receiver f_R is given by:

$$f_R = f_S \left(1 - \frac{\vec{U} \cdot \vec{l}}{c} \right) \quad (1)$$

where: c - speed of light in air, f_S – frequency of light emitted by the source.

- b) In the second case, the source is moving and the receiver is stationary. The observed frequency is given by:

$$f_R = \frac{f_S}{1 - \frac{\vec{U} \cdot \vec{k}}{c}} \quad (2)$$

In LDA, a stationary light source shines light which is then scattered by moving micro-particles and then recorded by the photodiode.

Combining the two equations above (1-2), gives the frequency of the scattered light detected by the stationary receiver (see Figure 9).

$$f_R = f_S \frac{1 - \frac{\vec{U} \cdot \vec{l}}{c}}{1 - \frac{\vec{U} \cdot \vec{k}}{c}} \quad (3)$$

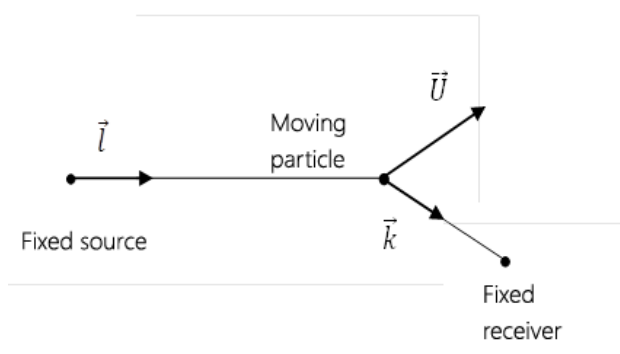


Figure 9. Light scattered by a moving particle.

Dual-beam anemometer

As a consequence of the Doppler effect, there is a small shift in frequency of the scattered light due to the movement of the micro-particles (as follows from Equation (3)) and direct measurement of the frequency (e.g. using a Fabry-Pérot interferometer) cannot be made with sufficient accuracy.

There are various methods to avoid direct measurement of optical frequencies.

Due to the square shape of the photodetector lines, it is possible to mix the two frequencies and record the beats in the resulting signal. For example, the method of self-beats where a shifted signal is mixed with itself (where the frequency measured is twice the frequency difference).

In Experiment 11, a double-beam configuration is used – two intersecting light beams from the same source.

A laser beam is split into two partial beams of the same intensity. Later, they are recombined and intersect at a certain point (mcv) (cuvette), where a flow of micro-particles in suspension cross the area where the beams intersect.

The Doppler shift of the scattered light is different for the two partial beams (different vectors \vec{l} , but the same vectors \vec{k}). This difference leads to the beat frequency.

The frequencies of the scattered light for each of the partial beams are given by:

$$f_{R1} = f_S \cdot \frac{1 - \frac{\vec{U} \cdot \vec{l}_1}{c}}{1 - \frac{\vec{U} \cdot \vec{k}_1}{c}} \quad (4)$$

$$f_{R2} = f_S \cdot \frac{1 - \frac{\vec{U} \cdot \vec{l}_2}{c}}{1 - \frac{\vec{U} \cdot \vec{k}_2}{c}} \quad (5)$$

The frequency difference (referred to as the Doppler frequency) is given as:

$$f_D = f_{R1} - f_{R2} = f_S \cdot \frac{\vec{U} \cdot (\vec{l}_2 - \vec{l}_1)}{c} \quad (6)$$

The frequency difference is significantly lower and has a narrower bandwidth than the frequency of the source, thereby allowing accurate measurement.

Using the relations in *Figure 10* and the relationship $c = f_S \lambda$ (λ – wavelength of the laser beam), the Doppler frequency can be expressed as follows:

$$f_D = f_{R1} - f_{R2} = f_S \cdot \frac{\vec{U} \cdot (\vec{l}_2 - \vec{l}_1)}{c} = \frac{\vec{U}_\perp \cdot 2 \sin \varphi}{\lambda} \quad (7)$$

where: \vec{U}_\perp – particle's velocity component perpendicular to the bisector of the angle between the beams.

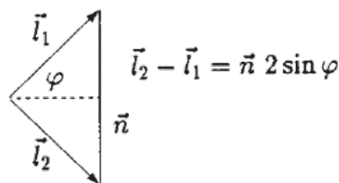


Figure 10. The difference in unit vectors (Phywe).

Knowing the Doppler frequency, we can calculate the particle velocity. Equation (7) shows that the velocity of a particle can be determined by measuring the Doppler frequency, if the particle passes through the cuvette (mcv).

$$\vec{U}_{\perp} = \frac{f_D \cdot \lambda}{2 \sin \varphi} \quad (8)$$

During the experiment, you can also determine the half-angle φ by measuring the distance from lens L1 to the plane of observation (l') and the distance between the two dots of light on the plane of observation (D) (Figure 2 in Appendix A). The angle φ is obtained as follows:

$$\operatorname{tg} \varphi = \frac{D}{2l} \quad \rightarrow \quad \varphi = \arctan \left(\frac{D}{2l} \right) \quad (9)$$

where: $l = l' - f$ (f – focal length of lens L1).

(B)

The principles behind LDA can also be explained by the use of Moiré fringes (or a fringe model) (Figure 11a, b).

In this model, two laser beams intersect and form parallel interference fringes at the cuvette (mcv). Small moving particles scatter the alternating constructive and destructive interference fringes. As a result, you can observe pulses with a frequency proportional to the velocity (component perpendicular to the grid), and inversely proportional to the distance between the fringes.

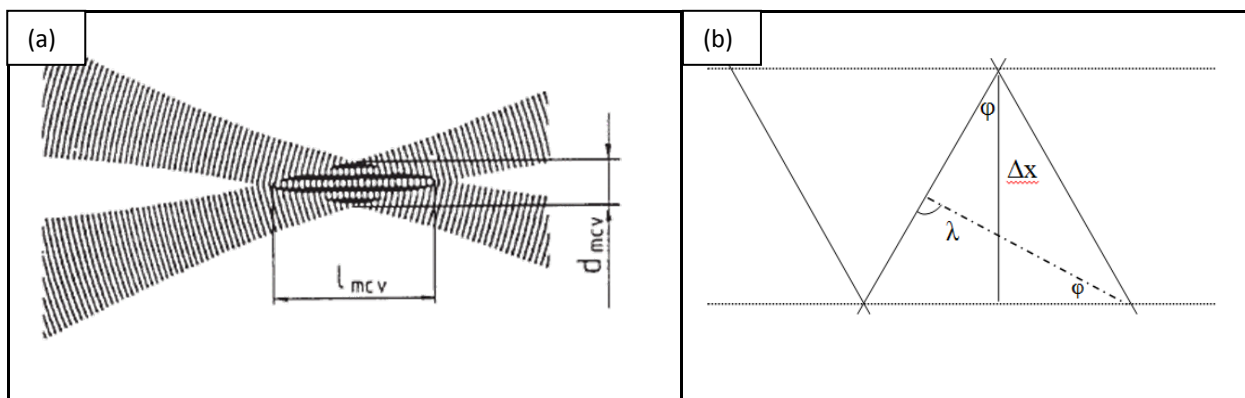


Figure 11. a) LDA fringe model (Phywe); b) Distance between interference fringes.

The frequency of intensity changes is given by:

$$f_D = \frac{\vec{U}_{\perp}}{\Delta x} \quad (10)$$

The distance Δx between fringes is given by:

$$\Delta x = \frac{\lambda}{2 \sin \varphi} \quad (11)$$

Finally, Equations (10) and (11) leads to Equation (7), which is used to calculate flow velocities.

To conclude – velocity measurements are reduced to measuring the radiation intensity changes over time. In the case of **(A)** we measure the beat frequency, in **(B)** we measure the frequency of the particles passing through the interference maxima formed by the intersecting beams [1].

The frequency can be found from the experimental results using the fast Fourier transform procedure (FFT) (reference [1] in the literature).