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FLOW MEASUREMENT OF FLUIDS  
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### LASER DOPPLER TECHNIQUES FOR FLOW MEASUREMENT

J. Oldengarm

Technisch Physische Dienst TNO-TH  
(Institute of Applied Physics)  
POB 155, Delft, the Netherlands

A brief review is given of the basic laser Doppler systems for flow velocity measurements. Different optical arrangements are discussed such as the reference beam mode, the forward scatter mode and the backscatter mode. A simple two-component optical system is described that is capable to measure two orthogonal velocity components simultaneously. Signal processing techniques being considered are frequency tracking, digital counting and photon count correlation. It is emphasized that there is no universal laser Doppler instrument that could be used for any flow measurement problem. Some application fields are discussed, for example flow velocity measurements in hydraulic engineering and flow field measurements in ship research.

#### 1. INTRODUCTION

The laser Doppler technique has become an important tool for measuring local flow velocities in many areas of science and technology. The principle of the Laser Doppler Velocimeter (LDV) is based on the measurement of the frequency shift in light scattered by small contaminant particles which are moving with the flow. The most striking advantage of the laser Doppler method is that the instrument does not disturb the flow field. Laser Doppler techniques can be used for a wide velocity range from the extremely slow motion in biological fluids to hypersonic speeds in wind tunnels. However, it must be emphasized that there exists no universal LDV system that can be used for any flow measurement problem. Many different LDV configurations exist and the flow problem to be attacked should be considered very carefully before a choice is made for a particular LDV-set-up. In many cases it is even necessary to construct a special LDV arrangement for a particular flow situation. In literature (1-3) numerous different LDV systems have been described for various applications. The aim of this paper is to give a brief review of the basic techniques together with some samples of applications.

#### 2. BASIC LASER DOPPLER SYSTEMS

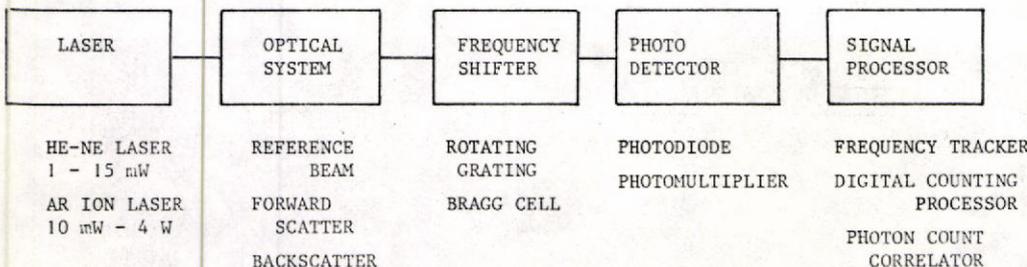
In general, a laser Doppler system consists of a laser source, an optical system, a photodetector and a signal processor. Additionally, a frequency shifter is needed in bidirectional velocity sensing is required. Many different components can be used for each of these basic elements.

A brief review is given in figure 1. The most widely used laser source is the He-Ne laser having a few milliwatts of light output power. In situations where the intensity of the scattered light is low a more powerful Argon laser can be necessary.

Many different optical configurations can be used for laser Doppler work. In most optical systems the beam from the laser is split into two parallel beams which are focused by a lens into the measuring volume as illustrated in figure 2. One can distinguish between forward scatter modes, in which only scattered light is directed to the photodetector, and reference beam modes in which scattered light is mixed with an undisturbed laser beam. In the latter case the sensitive area of the photodiode detector is positioned at the reference beam. The advantage of using the reference beam mode is the ease of optical alignment and it is found that this mode can be successfully applied for liquid flow systems in which many scattering particles are present. For flow systems with a low particle density, e.g. clean air flows, the reference beam mode is less suited and the forward scatter technique is then preferred. The reference beam mode is also very convenient to realize a two-component LDV system that measures simultaneously two orthogonal velocity components in one point. Rather complicated optics are needed to do this for other modes of operation.

In situations where the flow can be accessed only from one side the backscatter mode can be used. In this mode of operation the transmitting and receiving optics are situated at one side of the flow area.

Figure 1 Basic laser Doppler system elements



From practical point of view the backscatter technique seems to be the ideal method since then the complete optics, including the photodetector, can be built in a single package. However, it should be recognized that the intensity of backwards scattered light from small particles is about 100 to 1000 times smaller compared with the forward scattered light. This means that more laser power and more complicated electronics will be necessary to detect Doppler signals with backscatter techniques. For this reason the backscatter mode is not always the most ideal solution for every flow measurement problem.

If the sign of the velocity component being measured has to be recovered the optical system must be provided with a frequency shifter in order to give a pre-shift in light frequency for at least of one of the focused laser beams. Frequency shifting is accomplished by using a Bragg cell or a rotating radial diffraction grating. In systems having a frequency shifter a bias frequency shift is introduced in the Doppler frequency signal.

This bias frequency corresponds to zero velocity and then positive or negative velocities can be recognized as frequencies above or below this bias frequency.

Two practical optical arrangements are schematically shown in figures 3 and 4. Figure 3 shows a two-component reference beam system and figure 4 shows a coaxial backscatter system. Both systems use a rotating diffraction grating which functions as a beam splitter and as a frequency shifter. The use of rotating gratings in laser Doppler velocimetry is described in more detail in references (4) and (5).

Photodetectors suited for laser Doppler work are the photomultiplier tube or the photodiode. Although the photodiode is less sensitive than the photomultiplier it is very convenient in conjunction with the reference beam mode because the optical signal is already amplified by the heterodyning effect in the reference beam. The function of the photodetector is to convert the optical signal into an electronic signal.

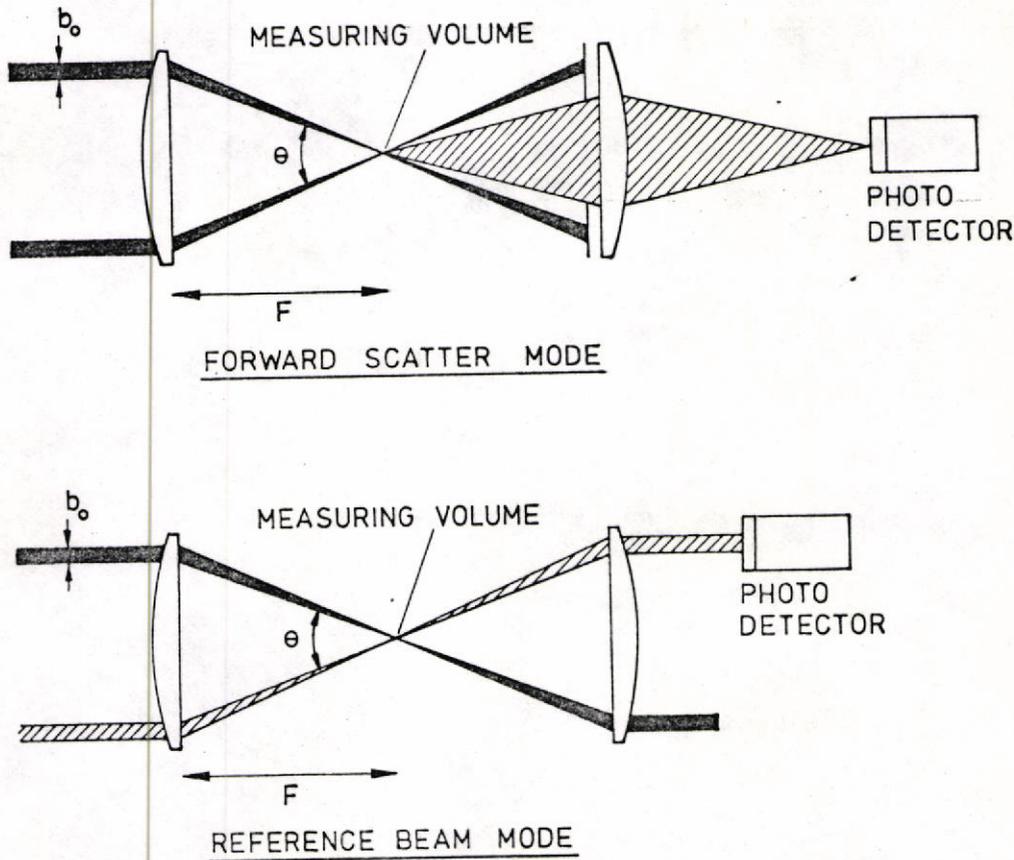


Figure 2 Basic configurations for laser Doppler systems

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This signal contains the velocity information in the form of a series of Doppler frequency bursts. Each burst corresponds to the passage of a particle through the measuring volume. Different types of signal processors are available that extract the velocity information from these frequency bursts. The most widely used processors are the frequency tracker, the digital counting processor and the photon correlator. The frequency tracker is based on the principle of wide-band frequency demodulation. This instrument produces an analog voltage at its output which is proportional to the instantaneous flow velocity.

Frequency trackers require a quasi-continuous Doppler signal. If this is not case, because the particle density in the fluid flow is too low, the digital counting processor can be used. This instrument utilizes the digital measurement of zero crossings in the Doppler frequency bursts. In certain circumstances the intensity of the scattered light can be such low that only a few photons per particle are detected, which makes it impossible to produce a frequency burst suited for real time signal processing.

In such cases the photon correlator will be of interest.

The principle of this instrument is based on the digital counting of individual photons. Velocity information is then extracted from the time averaged auto correlation function of the photon counts. The photon correlator provides only time averaged information about the flow velocity such as the mean velocity and, with some computations, also the turbulence intensity.

### 3. EXAMPLES OF APPLICATIONS

The TPD (the authors institute) has been involved in the field of laser Doppler velocimetry since 1968. Most of the work has been done on a contract basis for industrial and scientific laboratories. Many LDV systems have been built which are now in use at several laboratories. Other important activities of the TPD were the development of special LDV systems for unusual flow situations and the execution of measurement programs. Below, a brief review will be given of the most important application fields.

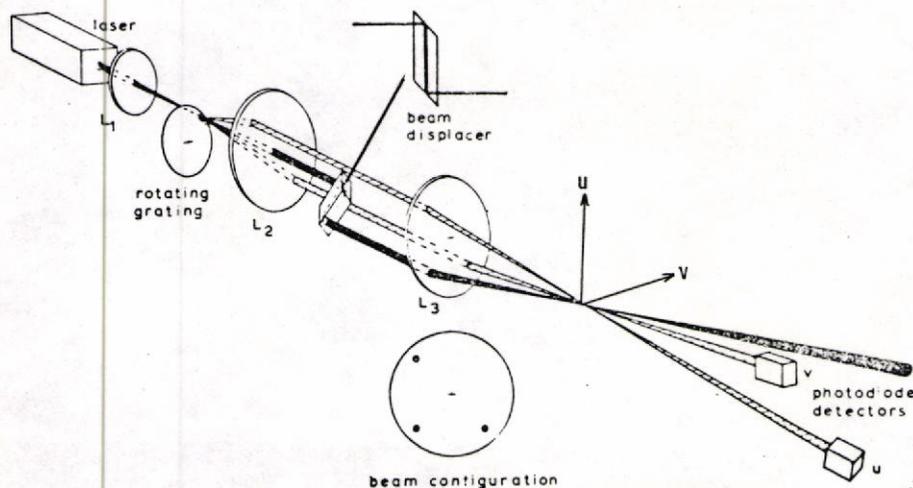


Figure 3 Optical system that measures two orthogonal velocity components simultaneously

### 3.1 Hydraulic engineering

In hydraulic research there are many flow measurement problems that can be attacked with the laser Doppler technique.

In particular non-steady flows are of interest such as waterhammer, the orbital movement in water waves and the velocity measurement in over-topping waves at a breakwater.

In most cases one requires the instantaneous flow velocity to be recorded. The use of a frequency tracker, in conjunction with a low power laser and a reference beam optical system is very suited for this type of work. However, it should be realized that transparent walls are needed for the hydraulic models in order to access the flow area of interest. The application of LDV techniques in hydraulic engineering is discussed in more detail by Godefroy (6).

### 3.2 Two-phase flows

Laser Doppler techniques can be used to measure velocities in two-phase flows. The main problem for this type of application is the interpretation of the measurement results. Many drop-outs occur in the Doppler signal and the essential difficulty is to distinguish between the signals received from each phase separately. An example of a two-phase flow application is the work by Goossens (7) in which entrainment and mixing phenomena in bubble columns are being studied.

### 3.3 Flow rate measurements in pipe flows

The laser Doppler velocimeter measures the flow velocity at a single point. To be able to compute the volumetric flow rate the complete velocity profile, or at least several points, have to be measured. Because single point measurements can be very time consuming we have developed an optical system in which the measuring volume is traversed through the test section automatically by moving the focusing lens by means of a constant speed electronic motor.

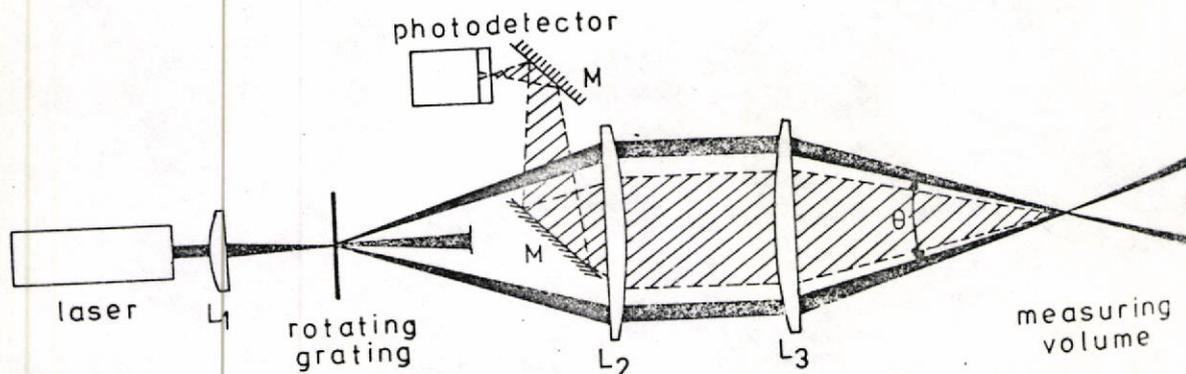


Figure 4 Optical system operating in the backscatter mode

In this way velocity profiles can be plotted quickly on a paper strip chart recorder. In cases where the flow profile is expected to be asymmetric, which occurs for example near bends, it is recommended to measure at least two velocity profiles in two orthogonal directions.

### 3.4 Ship engineering

During the last few years the TPD has put a lot of effort in the application of laser Doppler techniques for flow measurements in ship engineering. This work is done in close cooperation with the Netherlands Ship Model Basin (NSMB) at Wageningen. One of the major objectives was to develop an LDV system for measurements in the wake field of ship models. Experiments have shown that the three dimensional wake field can be measured by using a forward scatter reference beam system (8). Work is in progress to make such a system operational. Other experiments, also carried out at the NSMB, were directed to the use of backscatter techniques for those situations where it is impossible to apply the forward scatter mode. Results have been obtained with a photon correlator in conjunction with a He-Ne laser and with real time digital processing using a 500 mW Argon ion laser. Recently, backscatter LDV measurements have been made at a full scale ship during its voyage at sea. This vessel was provided with windows and velocity measurements were made near the propeller region. It was found, however, that provisions must be made to protect the fragile laser tube against the excessive vibrations that exist at full scale ships.

### 3.5 Thin film flows

In chemical engineering considerable attention is paid to the physics of phase boundaries in particular with respect to the mass transfer at interfaces in thin film flows. The laser Doppler technique is an ideal method to study flow phenomena in such tiny film flows since any other probe would drastically disturb the flow pattern.

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At the TPD special optics have been used to measure velocity profiles in thin film flows having a thickness of 0.1 mm to 1 mm. Measuring volumes with dimensions of about  $10 \mu\text{m} \times 30 \mu\text{m}$  have been realized (9).

### 3.6 Engine exhausts

At the TPD velocity variations have been measured in the exhaust of a diesel engine by using a frequency tracker and a simple reference beam optical system. It appeared that sufficient scattering particles were present in the exhaust gas to follow flow fluctuations properly. The experiments were done in connection with a noise abatement study for a ship engine.

### 3.7 Vibration measurements

The laser Doppler technique can also be applied for the remote and contactless measurement of mechanical vibrations. Low power lasers can be used because the light scattering by solid surfaces is much more intense compared with light scattering in fluid flows. For vibration measurements an optical set-up is used in which the target is illuminated with one laser beam while the backscattered light is mixed with a frequency shifted reference beam. In principle, the signal detected by the photodetector contains information about the target velocity, but other quantities as displacement and acceleration can be derived from the basic signal. The laser Doppler vibration meter is in particular suited for those situations where conventional transducers cannot be used for example because they would disturb the vibrational state or because the transducer cannot be attached to the object of interest.

### 3.8 Speed measurement of industrial products

The backscatter mode is also very suited for the velocity measurement of moving solid surfaces. This technique can be applied for many industrial processes where the speed of produced material has to be measured, in particular if a contactless method is required. A recent example is the speed measurement of copper tube during its production by hydraustatic extrusion. In this case information about velocity time history was needed for a better control of the production process. Other examples for which the LDV can be used are speed measurements at rolling mills in the steel and paper industry.

### 3.9 Some experimental results

Figure 5 shows a velocity profile of a laminar flow in an extreme small channel (only 0.4 mm wide) as measured with an LDV system. In this case the length of the measuring volume was about  $50 \mu\text{m}$  which is rather small compared with LDV systems in normal operation. The result illustrates that no reliable velocity data can be obtained in the wall region because of the

finite size of the measuring volume. As soon as the measuring volume reaches the wall the LDV system tends to measure zero velocity since the light scattering from the wall of the flow system is starting to dominate.

Figure 6 shows a velocity profile measurement in a pipe of 15 cm diameter. This result was obtained during flow rate measurements for a cooling system in which a certain type of oil was the flowing medium. At the test locations the pipe was provided with windows in order to be able to access to flow. The velocity profile shows a dip because of the convectional forces in this type of flow system. The "noise" in the curve shown in figure 6 is caused by the intense turbulent fluctuations superimposed on the mean flow velocity. Both results mentioned above have been obtained with a TPD Type 400 Optical System operating in the reference beam mode while using a 5 mW He-Ne laser. In both cases frequency shifting by means of a rotating grating was applied to detect the zero velocity of the flow boundary. Frequency to voltage conversion was achieved by using a TPD Type 1077 Frequency Tracker.

## 4. CONCLUDING REMARKS

The examples of applications given above show that the laser Doppler technique has become a widely accepted tool for flow velocity and speed measurements. In principle this technique can be used for any velocity measurement problem, provided that the medium or object to be investigated scatter sufficient laser light to detect Doppler signals and that the area of interest can be accessed optically.

Many LDV configurations are commercially available but it should be emphasized again that there is no universal LDV instrument. For some application fields work is still in progress. For example, at different places research is made to apply laser Doppler techniques for the remote sensing in the atmosphere. Although some results have been obtained remote sensing LDV systems are still in the laboratory stage.

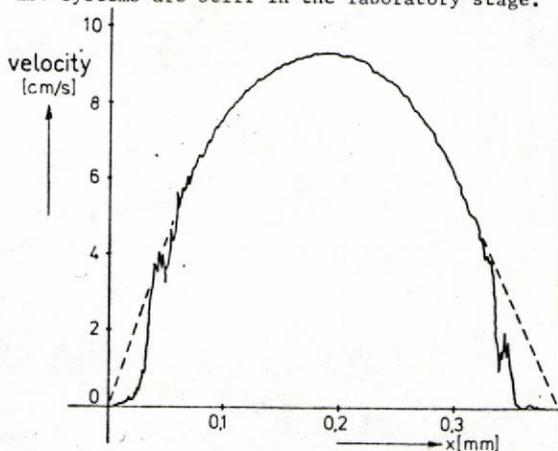


Fig. 5 Velocity profile measurement in a 0.4 mm wide channel

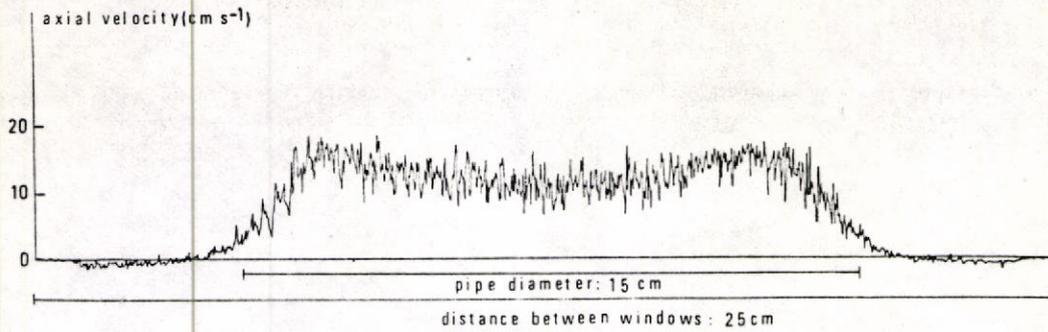


Fig. 6 Velocity profile measurement in a turbulent pipe flow

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