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Laser Doppler Anemometry and its Application in Wind Tunnel Tests

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Over the last 20 years, the leading technique of flow velocity measurements in the wind and water tunnels in the VTI, Belgrade, has been Laser Doppler Anemometry. In this article, the survey of the basic theory principles, the description and classification of different anemometers and the examples of application are presented.

Key words: **laser doppler anemometry, flow velocity, turbulence, wind tunnel, water tunnel.**

Introduction

LASER Doppler Anemometry (LDA) is the optical technique for investigation of velocity and turbulence in gas, liquid, and mixed fluids, flame, rotating machinery, in combustion, channels, chemically reacting flows, wave tanks, wind or water tunnels, in biomedical applications, atmospheres, oceanography and in various spectrum of scientific and industrial research where conventional techniques perform poorly [1-42].

The basic idea underlying LDA is to measure the velocity of tiny particles transported by the flow. If these particles are small enough, their velocity is assumed to be that of the stream and LDA provides a measure of the local instantaneous velocity, the mean velocity as well as the turbulent quantities. Fig.1 illustrates the basic LDA principles [1,-3, 5-7, 9, 13, 14].

Laser anemometers offer unique advantages in comparison with other fluid flow instrumentation [1-9, 14]:

- Non-contact optical measurement. LDA probes the flow with focused laser beams and can determine the velocity without disturbing the flow in the measuring volume. The only necessary conditions are a transparent medium with a suitable concentration of tracer particles (or seeding) and optical access to the flow through windows, or via a submerged optical probe.
- No calibration – no drift. The laser anemometer has a unique intrinsic response to fluid velocity–absolute linearity. The measurement is based on the stability and linearity of optical electromagnetic waves, which can be considered unaffected by other physical parameters such as temperature and pressure.
- Well-defined directional response. The quantity measured by LDA is the projection of the velocity vector on the measuring direction defined by the optical system.
- High spatial and temporal resolution. The optics of the laser anemometer is able to define a very small measuring volume and thus provides good spatial resolution and allows local measurement of velocity. The small measuring volume in combination with fast signal processing electronics also permits high bandwidth, time-resolved measurements of fluctuating velocities, providing excellent temporal resolution.
- Multi-component and multi-directional measurements. Combinations of laser anemometer systems with component separation based on color, polarization or frequency shift allow one, two or three-component LDA systems to be put together based on common optical modules. Opto-acoustical frequency shift allows the measurement of reversing flow velocities.

Figure 1. Illustration of the LDA principles [6]

These properties of LDA constitute together a very attractive description of a measuring instrument. LDA has a lot of advantages, but some of the compromise decisions have to be made when selecting and setting up laser anemometer systems. For example, the postulate of LDA (and any other method using seeding particles) is not always true in highly decelerating or accelerating flows.

The special properties of the gas lasers (high energy, spatial and temporal coherence and stability) make this method applicable for a large number of problems. The principles and applications of LDA will be described further on.

Theory of Light scattering and Doppler Effect

Doppler Effect is a well known effect discovered in nineteenth century by physicist Doppler [1-3, 9-11, 14]. If a body moving towards the source is illuminated by a light wave, the body will see light with a higher frequency than

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that initially emitted. When the body scatters the light, it reemits light of the same frequency as it receives. The fractional shift in frequency of scattered light is approximately $2V/c$, where V is the velocity of the body, and c is the velocity of light. (The frequency of the light is f=5 10^{14} Hz, and the Δf of scattered light by body with V= 1 m/s, is $\Delta f \approx 0.3\ 10^6$ Hz). This shift is called Doppler frequency and depends on body velocity. It can reach the amount of same hundred MHz, if the velocity of the particles is very high. The shifted light may be analyzed directly by spectrometric methods, or by LDA (differential method, reference beam or interference fringes method).

Gas lasers operating in the fundamental optical mode (TEMoo), are ideal sources for Doppler shift measurements. Laser light can be focused to the small spot and all laser energy can be concentrated in it. When particles go through the beam crossing, they scatter light in all directions. This scatter light can be collected from any direction by a detector.

If the vector $\vec{V}$ represents the particle velocity, the unit vectors e_i and e_s describe the direction of incoming and scattered light respectively. According to the Lorenz-Mie theory [10, 11], the light is scattered in all directions at once, but it considers only the light reflected in the direction of the receiver.

The incoming light has the velocity c and the frequency f_i. From the receiver point of view, the seeding particles act as moving transmitters, and the movement introduces additional Doppler-shift in the frequency of the light reaching the receiver f_s. Using the Doppler theory, the frequency of the light reaching the receiver can be calculated as:

$$f_s = f_i \frac{1 - e_i \frac{V}{c}}{1 - e_s \frac{V}{c}} \tag{1}$$

Even for supersonic flows the particle velocity $|\vec{V}|$ is much lower than the speed of light, meaning that $|V/c|$<<1. The expression (1) can be approximated to:

$$f_s = f_i \left[1 + \frac{V}{c}(e_s - e_i) \right] = f_i + \frac{f_i}{c} V (e_s - e_i) = f_i + \Delta f \tag{2}$$

The particle velocity $\vec{V}$ can be determined from the measurements of the Doppler shift Δf (2).

In practice this frequency change can only be measured directly for very high particle velocities (Fabry-Perot interferometer). If two intersecting laser beams illuminate the particle, both incoming laser beams are scattered towards the receiver, but with slightly different frequencies due to the different angles of the two laser beams.

$$f_{s1} = f_1 \left[1 + \frac{\vec{V}}{c}(\vec{e}_s - \vec{e}_1) \right]$$

$$f_{s2} = f_2 \left[1 + \frac{\vec{V}}{c}(\vec{e}_s - \vec{e}_2) \right] \tag{3}$$

When two wave trains of slightly different frequency are super-imposed, it results in the phenomenon of a beat frequency due to the two waves intermittently interfering with each other. The beat frequency corresponds to the difference between the two-wave frequencies, and since the two incoming waves originate from the same laser, they also have the same frequency, f_1=f_2=f_i. This gives the general equation expressing the Doppler shift f_d, in the frequency of the scattered light as a function of particle velocity $\vec{V}$ (v_x; v_y; v_z):

$$f_d = f_{s2} - f_{s1} = f_i \left[\frac{V}{c}(e_1 - e_2) \right] = \\ = \frac{f_i}{c} \left[|e_1 - e_2| \cdot |V| \cos(\varphi) \right] = \frac{2\sin\left(\frac{\theta}{2}\right)}{\lambda} v_x \tag{4}$$

There λ is the light, the wavelength θ is the angle between the incoming laser beams and φ is the angle between the velocity vector $\vec{V}$ and the direction of measurement. The unit vector e_s is dropped out of the calculation, meaning that the position of the receiver has no direct influence on the frequency measured. But, according to the Lorenz-Mie theory [1, 10, 11] the position of the receiver will however have considerable influence on the signal strength. The beat-frequency, also called the Doppler-frequency f_d, is much lower than the frequency of the light itself, and it can be measured as fluctuations in the intensity of the light reflected from the seeding particle. As (4) shows, the f_d is directly proportional to the v_x of the particle velocity, and the v_x can thus be calculated directly from f_d:

$$v_x = \frac{\lambda}{2\sin\left(\frac{\theta}{2}\right)} f_d \tag{5}$$

There are a lot of different set-ups of LDA. In the reference beam mode, the light scattered from one laser beam is mixed (heterodynes) in the photo detector with the light from a reference beam (with original laser light). This is done by a coaxial superposition of the scattered beam and the reference beam at the photo detector. In the differential Doppler mode two laser beams of equal intensity intersect in the measurement point. The light scattered from any direction is picked up by the photo detector. The f_d is the difference between the two scattered frequencies and it is independent on the direction of positioning of the receiving optics.

The most used method is a fringe model laser Doppler anemometer (Fig.1). It will be described there, because that configuration is the base of anemometers used in the VTI laboratories. A laser beam is divided into two parallel beams of equal intensity by a beam splitter. By means of transmitting optics with the focal length f, the two beams intersect each other in the focal point of the optics forming the angle θ/2. Two laser beams are coherent and monochromatic and the interference fringes are formed at the beam crossing (Figures 2a and 2b). The distance between fringes δ_f is:

$$\delta_f = \frac{\lambda}{2} \sin\frac{\theta}{2} \tag{6}$$

If the small particle (small compared with the δ_f) velocity component perpendicular to the fringes is v_x, the time needed to pass through the one bright fringe is $t=\delta_f/v_x$. When the particle passes the bright fringes, the light is scattered. The scattered light, collected of the photomultiplier is Doppler shifted. The Doppler frequency f_d will be:

$$f_d = \frac{v_x}{\delta_x} = \frac{2v_x}{\lambda} \sin\frac{\theta}{2} \tag{7}$$

The photomultiplier converts the received light, oscillating in intensity, into an electrical signal. The frequency of the photocurrent corresponds to the f_d. The typical laser Doppler burst is given in Fig.2b.

Optical Components and Modules in Standard LDA Systems

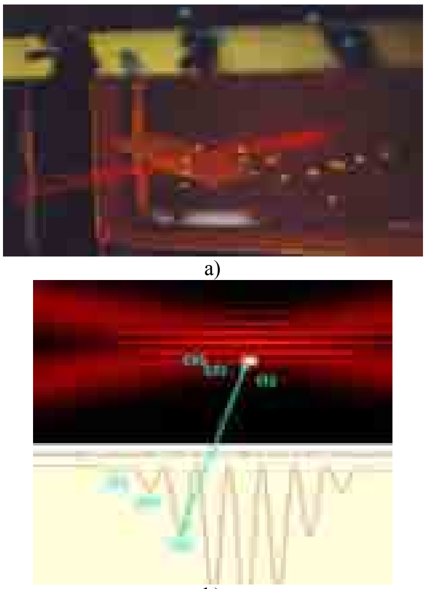
Laser Doppler anemometers are designed as compact or modular systems, with fiber optics or classical, for large distance and large area measurements or for microscopic applications [1, 4, 6, 18]. The modular systems are very often used because they can be adapted to the mode and configuration most suited for a particular measurement. The modules are optimized for the maximum signal to noise ratio (SNR) for the detected signal.

The simplest is the one-component LDA system (1DLDA), in forward mode shown in Fig.3. It can measure only one component of velocity up to 300 m/s. A laser source (1) is usually the up to 15 mW power He-Ne laser. The optical system for transmitting and receiving the signal (2, 3) and the photo detector (5) are the main parts of LDA. The optical system contains the beam splitter and various prisms for directing the beams, beam waist adjuster, a pair of $\lambda/4$ plates, beam translator, front optics with different focal length, and optical beam expander.

The Bragg cell module serves to introduce a fixed frequency difference between two laser beams, the "frequency shift". The f_d will be added or subtracted from this shift. The backscatter section consists of a 45° mirror and the PM optics with the pinhole spatial filter and the interference filter matched to the laser line.

Two velocity components can be measured simultaneously by one color laser beam with different polarizations, or with two color laser beams (coming in the probe volume, and forming two independent orthogonal interference fringes).

A totally new concept in LDA for turbulence studies is found in the devices such as the Flow Explorer [8]. The laser and optics are integrated into one robust and compact unit that features easy exchange. The Flow Explorer is capable of measuring flow reversals and zero velocity typical of highly turbulent flows.

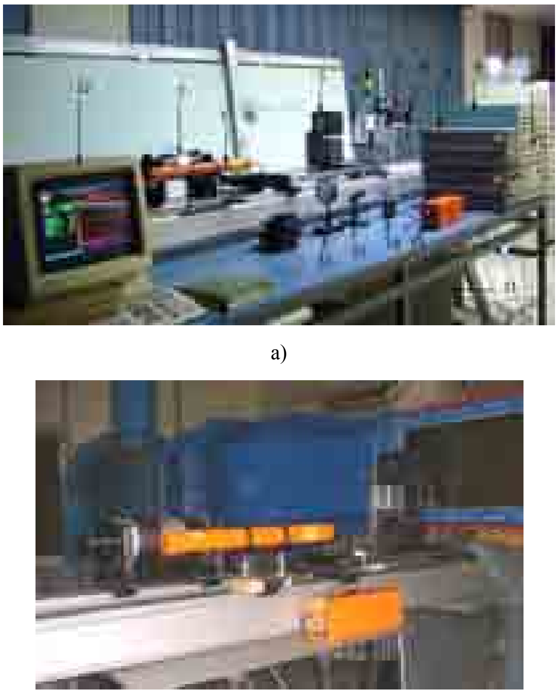


a)

b)

Figure 2. Measuring volume, a) intersection of 1D LDA laser beams in the test section of the water tunnel T-33, b) zoom of the measuring volume and the Doppler burst [33, 39, 40]

The LDA systems for the optical investigation of water flows are commercially available. They have compact watertight probes (Fig.4d) [6], which can be placed directly in a tank/basin. A wide range of front lenses permits great flexibility in selecting the distance from the probe to the measurement point and a side-looking section and orientation of the LDA probe parallel to the streamlines.



a)

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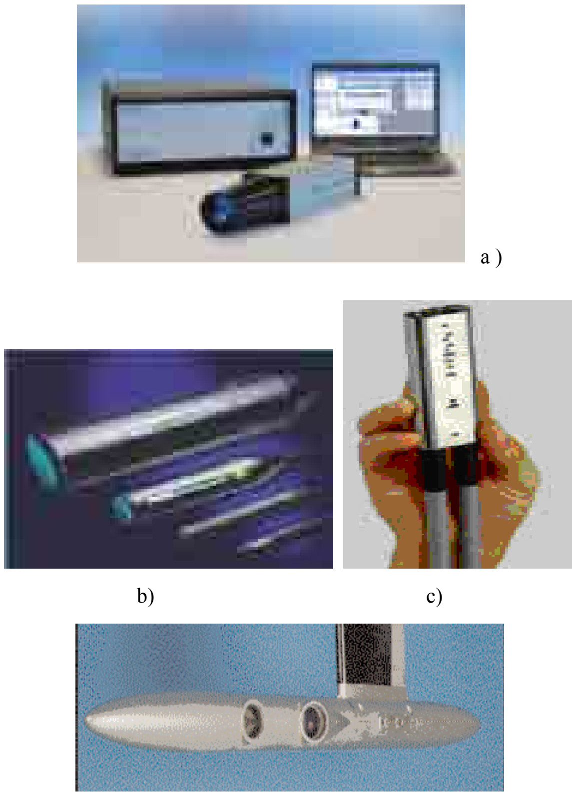
Figure 3. 1D LDA system, a) in laboratory and b) alongside the VTI water tunnel



a)

b) c)

d)

Figure 4. LDA systems: a) Flow Explorer system [8], b) Fiber Flow transmitting/receiving optics with different diameters (14-112 mm), c) mini LDA system, and d) Dantec 80 mm diameter submersible LDA probe [6]

In the reference [21] t a multi-component Laser-Doppler Anemometer is presented. The channel separation in it is based on a new method of using the coherence properties of different semiconductor lasers, one for each LDA beam.

The design of a three-component (3D) LDA system is based on three different colors in Ar-jon laser light (Fig.5a) or on using two lasers with different colors (Fig.5b) [1, 2, 4, 6, 11, 13]. There is a lot of variation in optical modules, in space location and configuration. The best choice is using the one-component system, placed orthogonally to the two-component system. Of course this gives the best conditions to measure the third velocity component, but unfortunately it is not practical with regard to a large wind tunnel. The often used choice is the three-component systems with two optical channels and the angle between them less than 90^{o} [6].

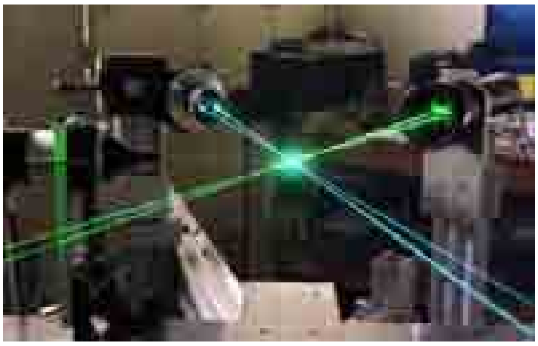
Three LDA systems are used in the VTI laboratories, the first one is the one- component, and the second one is the two - component LDA (separation of two components of velocity is achieved by polarization of the He-Ne laser light). It can be used in the velocity range up to 300 m/s, with the measuring point up to 0.6 m from the front lens.

The third system is the 3D LDA, designed for the VTI T-38 wind tunnel [12-15]. It is based on three colors of the 5W Ar-jon laser. The 5-beam optics is built in two optical systems placed side by side on a common base with an Ar-jon laser. One optical system is used as a transmitter of radiation with λ= 476 nm, and receiver of radiation with λ= 488 and λ=514 nm. The second one, receives λ = 476 nm, and transmits the λ = 488 and 514 nm. Mirrors and prisms direct the beams leaving the transmitters to a common probe volume (Fig.6a) at a suitable angle to resolve three simultaneous velocity components (Fig.6b). The 2D-probe still measures the velocity components u_1 and u_2, while the 1D-probe measures the velocity component u_3. The optical axes of both probes still lie in the v-w plane, and u_1 still corresponds to the desired vertical velocity component u exactly, but horizontal velocity-components are now measured differently.

For example in Fig.6b, both probes measure off axis, being aligned symmetrically on either side of the w-axis, requiring a transformation matrix (8).

$$C = \begin{vmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{2\cos\alpha} & \frac{1}{2\cos\alpha} \\ 0 & \frac{1}{2\sin\alpha} & \frac{-1}{2\sin\alpha} \end{vmatrix} \qquad (8)$$

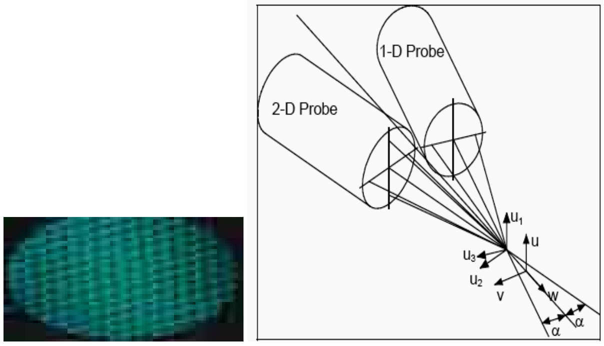
Transformation equations (8) are a transformation matrix, the element of which contains all the geometrical parameters of the optics that are necessary to convert three measured Doppler frequencies to three orthogonal velocity components.



a)

b)

Figure 5. 3D LDA (a and b), systems measuring three components simultaneously with different color beams [6,16,18]



a) b)

Figure 6. Microscopic image of the measuring volume a) and geometry of a 3D LDA system b).

The 3D LDA system in the VTI [9, 12, 14, 15, 19] is capable of measuring the velocity up to 650 m/s. The optical configuration and traversing system have been developed to reach every point in the test section. Besides standard optical components, two 1800 mm beam expanders are used. The angle between the optics is 20^{o}, the expansion ratio 3 and the beam intersection angle 1.98^{o}. The spectra physics laser model 2020-05 Argon-jon is the light source. The traversing system can be local and computer controlled. The range of traversing is x=950, y=660 z=600mm with a velocity of 75m/s. The signal acquisition and processing systems are based on the counters and the PDP 11/73 micro computer.

Accuracy of 3D LDA measurements depends on a lot of conditions. The geometrical setup of optical components is very important.. The on axis component of velocity is dependent on the angle between both modules (1D probe and 2D probe) and on the angle between flow velocity and the LDA optical axis [1, 4, 15].

The spatial resolution of the velocity profile is limited in principle by the size of the probe volume. A conventional solution for a better resolution in 3D LDA systems is to use the coincidence window technique to evaluate only signals of at least two velocity components that appear in a given time interval and thus decrease virtually the size of the probe.

The new method described in [18] allows improvements of the spatial resolution by at least one order of magnitude and small-scale velocity profiles measurements inside the measuring volume of a commercial available 3D LDA.

LDA Parameters

The most important parameters of LDA systems relate to the calibration constant C, the dimensions of the measuring volume and the number of interferometric fringes and the need to input parameters such as laser wavelength, beam waist, LDA beam separation, beam expansion and measuring distance [1, 4, 5, 14].

The measuring volume is defined as the region in the space from which Doppler signals are received and detected by the system. It looks like an ellipsoid for the laser beams with the Gaussian intensity profile. The probe volume parameters are:

$$d_x = \frac{d_f}{\cos\frac{\theta}{2}}, \quad d_y = d_f, \quad d_z = \frac{d_f}{\sin\frac{\theta}{2}} \tag{9}$$

Where d_x, d_y, d_z are the orthogonal axes of probe ellipsoid, d_f is the diameter of the focused laser beam, is the angle between the laser beams.

$$d_f = \frac{4}{\pi}\frac{f\lambda}{Ed} \tag{10}$$

d is the diameter of the laser beam waste before expansion and λ is the laser wavelength. If E is the beam expansion factor, the fringe number N is:

$$N_f = \frac{8}{\pi}\frac{f}{Ed_i}tg\frac{\theta}{2} = \frac{4D}{\pi d_i} \tag{11}$$

D is the beam separation before expansion. The distance between the fringes in the probe volume is:

$$\delta_f = \frac{\lambda}{2\sin\frac{\theta}{2}} \tag{12}$$

The calibration factor of the LDA system is: $C = \delta_f$

$$C = \frac{\lambda}{2\sin\frac{\theta}{2}} \tag{13}$$

The Doppler frequency measured with the LDA system with the calibration factor C is:

$$f_d = \frac{v_x}{C} = \frac{2v_x}{\lambda}\sin\frac{\theta}{2} \tag{14}$$

The measuring volume is influenced by many system parameters and usually differs from the probe volume. The most important is the influence of the detector optics.

The measurement of a particle velocity $\vec{V}$ can only be carried out within the section of the probe volume "seen" by the receiver optics, and depends on the angle between the LDA optical axis and the receiver axis. Doppler ambiguity noise is closely related to the size of the measuring volume (9).

Measuring values

In the 3D measurement, five or six laser beams are focused in the same point, where they form three independent fringe systems. A particle crossing the probe volume scatters three-color light which is detected by three photo detectors and processed in the three-channel devices. Optical adjustments of an LDA system where the channels are non orthogonal is a critical step in ensuring the instrument will provide mean velocity measurements with low systematic uncertainties.

For obtaining the flow velocity vector from the measured f_d, the following must be known: semi angle between the beams of one color crossing the measuring volume, angle between the horizontal plane of the measuring platform and the measuring plane formed by one pair of beams, and semi angle between the two optical axes. To get the lateral velocity component, a third measurement is required along an optical axis different from the axis of the other two components. To maintain the whole optical equipment compact and mechanically stiff, the angle between two optical axes should be as small as possible. On the other hand the resolution and accuracy of the cross flow component will become better with the increase of the coupling angle. A resolution of the cross flow component of 1% of the main flow velocity is desired [4, 15].

The final parameters in LDA measurements (the mean velocity V_m, the root mean square RMS and the turbulence T) can be calculated with the next equations:

$$Vm = \frac{\sum_{i=1}^{N} Vi}{N} \tag{15}$$

$$|\Delta V| = |Vm - Vi| \tag{16}$$

$$RMS = \frac{1}{N}\sqrt{\sum_{i=1}^{N}|\Delta Vi^2|} \tag{17}$$

$$T(\%) = \frac{RMS}{Vm}100 \tag{18}$$

Seeding

Particles in the flow are the scattering centers for LDA and they have important role in measurements [1, 3-6, 9-11, 17, 37, 38]. The ordinary particles in the wind tunnel are not sufficient to satisfy the requirements of LDA measurements. The natural concentration of particles is dominant out of useful range, and causes most often an undesirable shot noise level. It is recommended, whenever possible, to control the sizes and concentration of the seeding particles by filtering and subsequent addition of known seeding particles. Small particles (diameter compared to the wavelength of light λ) are of most interest in laser anemometry. The angular distribution of the light intensity depends on particle size, refractive index and shape. The scattered light intensity is much smaller in a backward then in a forward direction, if a particle diameter is large compared to λ. The scattered light intensity is distributed isotropic as predicted by the Raleigh theory [1, 6, 10, 11], if the particle size becomes small enough. For larger particles the Mie scattering theory predicts no isotropy. The forward scatter intensity increases with increasing the particle diameter but the backscatter intensity remains almost the same.

There are different methods and devices for particles seeding in wind tunnels [1-7, 19]. Materials used for particle generation may be: water, silicon oil, DOP, teflon dust, PVC, titanium dioxide, aluminum, aluminum dioxide, ammonium chloride, stannic chloride, tobacco smoke, magnesium oxide, smoke bombs, smoke pellets, ice. Generation of particles is based on: atomization, fluidization, chemical reaction, combustion and sublimation. The diameter of particles may be between 0.03μ to 10μ. The particles suited for water are: air bubbles, hydrogen bubbles, polystyrene, latex, fluorescent latex, aluminum powder, plastic paint, etc.

The particles have to be much smaller than the micro scale of turbulence, but large enough to avoid any noticeable influence of the Brownian motion [22]. The optical demands also determine the optimum value of the particle concentration in the fluid. For $r \sim 1\mu$ one obtains an optimum of $7 \cdot 10^6$ cm^{-3}.

Seeding generators are commercial devices or devices specially developed for wind or water tunnels [1, 3, 9, 15]. A seeding generator with Al_2O_3 powder has been developed in the VTI laboratory and inserted in the setting chamber in the trisonic wind tunnel. Seeding particles have to be injected into the flow upstream of the test section to ensure the particles will follow the airflow [19].

Signals and Data Processing

The photo multiplier section (PM) can be used both in the backscatter and the forward mode. The PM optics is used to collect and focus the scattered light into a pinhole and direct it through a filter to a PM. It can be focused from 80 mm to ∞. The PM optics is designed in such a way to reduce the amount of unwanted reflected laser or ambient light reaching the detector.

The primary result of a laser anemometer measurement is a current pulse from the photo detector. This current contains the frequency information relating to the velocity scattering centers. The photocurrent also contains different noises (shot, secondary electron noise and preamplifier thermal noise) [1-8].

Very important for the quality of the signal and the performance of the system is the number of simultaneously seeding particles in the measuring volume. One particle in the volume, gives a "burst type Doppler signal". If more particles are presented in the volume simultaneously, there exists a "multi particles signal ". In that case, the PM current is the sum of the current bursts from each individual particle into the illuminated region.

The LDA systems with counters are used in the VTI laboratories. In principle, the counter is simply a timing device or a stopwatch. The LDA counter can be set to measure the time for 8 zero crossings, or to measure the time for all periods of a burst above a certain trigger level. Although the primary measurement is a time measurement, the number of signal periods allows easy conversion to frequency. The interval between bursts may also be measured.

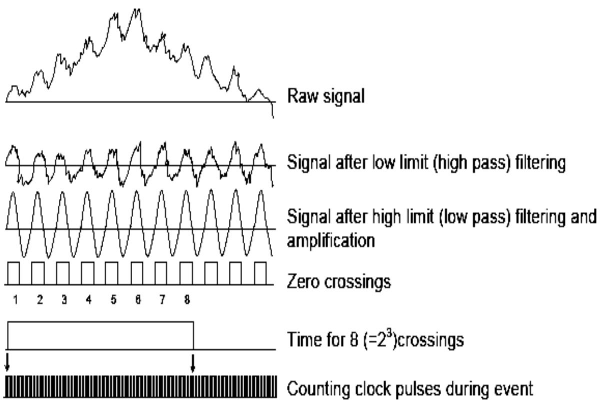


Figure 7. Illustration of the counter principles.

The LDA systems with counters are used in a situation where low seeding particle concentration occurs as in wind tunnels measurements, large water channels, two phase flows, or where seeding concentration is difficult to control.

The counter is a completely digital instrument. To use the instrument in a proper way, a very fast digital data transfer to the computer must be available. The buffer interface fulfills the requirements and allows simultaneous connection of three signal processors, traversing electronics and other external equipment. Fig.7 shows an illustration of how the counter processor gives a digital count of the time for 2^3 fringe crossings [6].

The Burst spectrum Analyzer (BSA) is a new signal processor, able to process Doppler signals under conditions where conventional processors (counter, tracer, photon correlator) fail. The BSA is based on the use of the Fourier transform as a method to extract the Doppler frequency. The BSA has high accuracy, wide frequency range, acceptance of poor S/N ratio, processing of both single burst and continuous signals. It is fully computer-controlled. For this purpose a powerful software package is available [6].

Disadvantages of LDA

The homogeneity, damages and stresses of glass window may produce light refraction and dislocation within the measured volume, which must be taken into account during fluid velocity measurement.

While the development and use of LDA marks a significant improvement in ability to measure flow properties in a way that will not directly influence these properties through the presence of a probe within the flow being measured, LDA is not without its disadvantages. Perhaps one of the largest disadvantages to using LDA for large scale wind tunnel experiments is the time and effort required to map out a large portion of the flow field around and behind the body of interest.

Our experience shows that LDA has a lot of advantages compared to classical methods, but there are some problems concerning to seeding, choosing of the LDA configuration for some complex flow fields, signal processing with counters, minimization of S/N ratio, elimination of model and system vibration, etc. Optical visibility of flow is required i.e. a part of the wind tunnel wall must be visible. Dirty wind tunnel windows or airflow itself can produce high level of noise and after signal reduction can be registered as a dummy high turbulence level.

Experimental examples

A lot of tests using LDA have been performed in the laboratory of experimental aerodynamics. Some results will be presented here as an illustration of LDA - the applications in wind and water tunnels [20-40].

Rotating disk

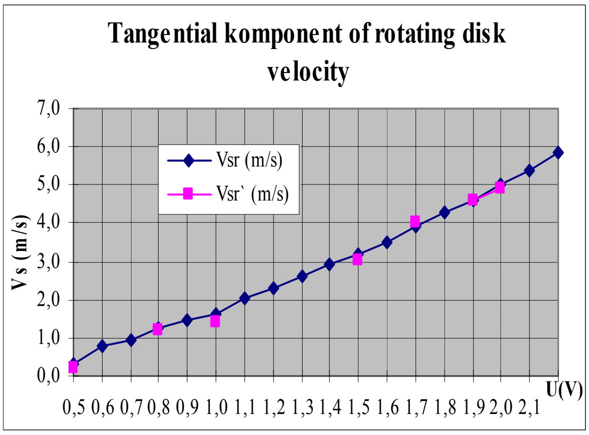
Calibration of an LDA device is not required because the calibration constant *C* (13) is defined with the light wavelength and the intersection angle of the laser beams, but system adjustment can be checked by the calibration rotating disk [20].

The laser beams were carefully focused onto the edge of a rotating disk of a precisely known diameter (Fig. 8a). The rotational speed of the disk was also precisely known, thus establishing a well-defined surface velocity at the circumference of the disk (Fig.8b). The fringe spacing df (and the half angle, K), was calculated from the LDA reading and the actual surface velocity of the disk.

Calibration of the wind tunnel test section

The results of calibrating the test section of the trisonic wind tunnel (T-38) with the 3D LDA system are shown in Fig.9. The test has been carried out along the radius vector downstream of the attached oblique shock wave, generated around the con top. The measured results are compared with the theoretical values (dotted line) [12].

a)



b)

Figure 8. Experimental set-up a) and the disk calibration diagram b)

As the running time of a large wind tunnel is rather expensive, the operational application of the LDA instrumentation requires a sophisticated performance and reliability. This implies a fully automatic measuring run, which includes high measuring speed, quick achievement of a new measuring station within the flow field under test, such as a traverse of LDA along new coordinates by a computer-controlled traversing mechanism. Likewise data acquisition, data reduction, providing a quick-look-result and storing the data, has to be performed in a computer-controlled way and automatically.

The application of laser Doppler anemometry is of considerable interest in large wind tunnels for determination of characteristic flow properties such as velocity, vorticity, turbulence, and shear stress. The problem is that in the case of large wind tunnels the running time is expensive, and the operation conditions are rather unsuitable and there LDA has to fulfill requirements other than those under laboratory conditions [7, 12, 19, 20-22].

First of all, there is a large measuring distance. The signal to noise ratio is decreased with the 4th power of the distance. To optimize that, the laser intensity as well as the aperture of the receiving optics has to be increased. But lasers with large power are non stable in the Gaussian mode and the optics with large apertures is very expensive. To avoid this disadvantage and to achieve the necessary improvement in sensitivity and to reduce the amount of unwanted scattered light, the forward arrangement can be used. Very often off-axis set-ups are preferred as long as measuring distance is not too large. The direction of transmitting the light of one color is separated from the direction of observation, thus the receiving optics can only collect light of the specific color which is scattered into the solid angle of the receiving optics.

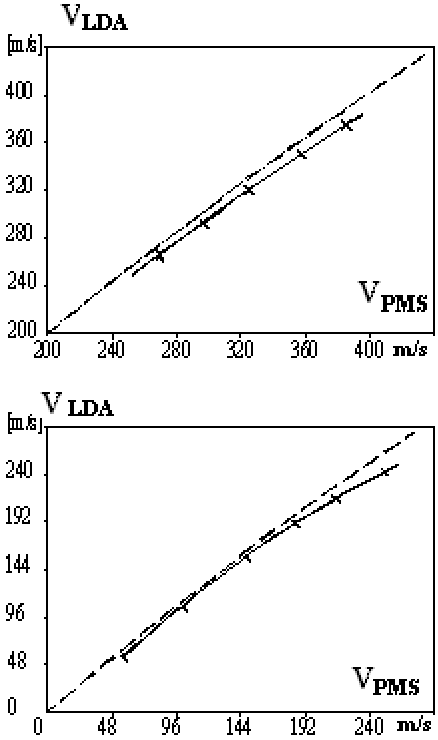


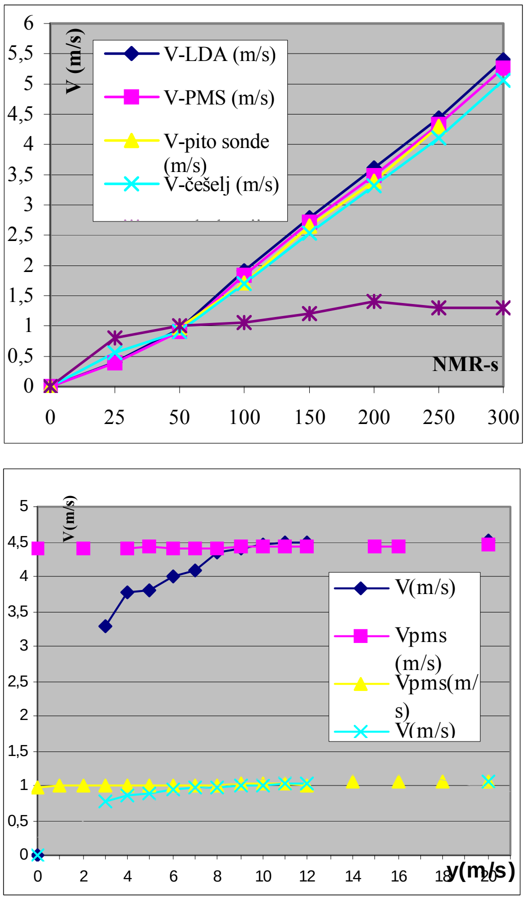
Figure 9. Calibration of the T-38 wind tunnel test section with the 3D LDA system

A second consideration is that of vibrations either of the housing of the wind tunnel, the model or the optical system of the LDA itself. To optimize the measuring condition (when the distance is large), the "collecting volume" of the receiving optics has to coincide continuously with the measuring volume produced by the transmitting optics. If the stability is not ensured, the two different volumes coincide merely randomly in time and the sample rate will be decreased due to the mechanical vibrations. In order to avoid uncorrelated vibrations, the transmitting and receiving optics have to be mounted closely together on a rigged table.

A number of experiments have been performed in the T-36 wind tunnel with 1 and 2D LDA [26, 27].

Calibration of water tunnel test section

The calibration of the water tunnel was made with the 1D LDA system. The velocity distribution across the cross section (top to bottom, left to right) in different points was measured. The velocity profile within the wind tunnel is flat. Special attention is paid to measurements in the boundary layer. Fig.3b shows the LDA system in the water tunnel. The results are represented in Figures 10a and 10b [21, 22].



a)

b)

Figure 10. Calibration of the water tunnel: a) Comparative calibration diagrams *V=f* (number of motor rotations per minutes), b) boundary thickness measured by LDA and PMS in the water tunnel [24, 25, 39, 40]

Measurement in the flow with near zero velocity

The advantages of LDA with a combined optical and electronic frequency shift for turbulent flows of near zero mean velocity are illustrated by the results of tangentional velocity component of circular water flow measurements, without and with frequencies shifts [25, 31]. Fig.11 is the photo of the experimental set up (2-optical modul, 3-front lens, 4-cilindrical container, 5-PM optics, 6-PM, 7-electrical mixer). The water has been mixed by hand and by an electrical mixer. The measuring volume was 2 cm from the center line.

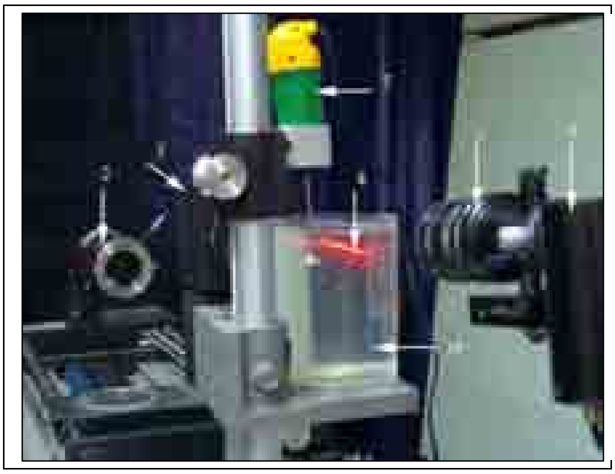
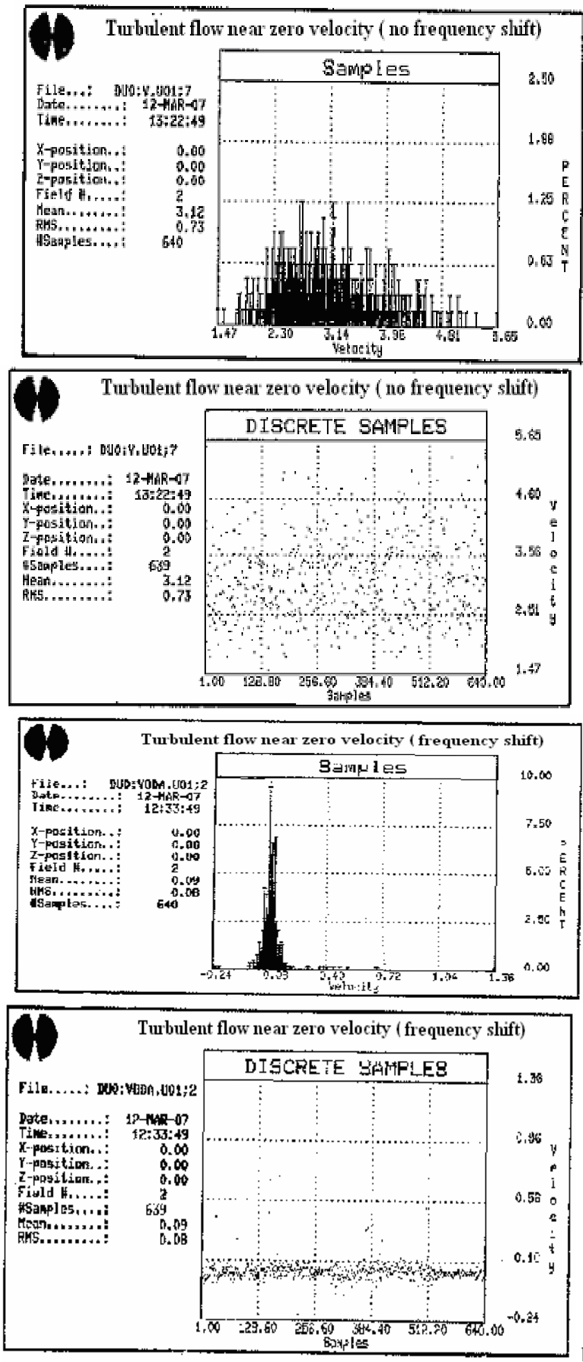


Figure 11. Set up for the measurement of near zero velocity of the water in the cylindrical vessel

Fig.12a shows the measurement results without frequency shift V_m=3.12m/s and RMS=0,73. The real value of mean velocity is V_m=0.09m/s and RMS=0,08 (Fig.12b). It is obtained when the frequency shift is used [26].



a)

b)

Figure 12. Histograms of tangentional velocity components of the circular water flow and the time distributions of the measured values (without and with frequencies shift) [26]

The measurement in tube with a complex shape

In many applications of LDA, flows in tubes with complex or circular cross sections are investigated. The refraction of the incident laser beams on curved (glass or plastic) walls may produce the dislocation of the measuring volume and the changing of the calibration constant of the system. There are different ways to diminish the influence of that problem and make correct measurements [8, 27-32, 42].

Fig.13 shows some type of the tubes used in the experiment and Fig.14 shows the results obtained for horizontal velocity component V_h along the tube axis.

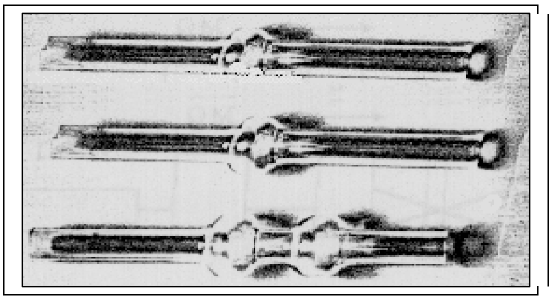


Figure 13. The tube with different shapes [32]

The diagram of the measured values v_x versus the tube length is on the upper side, the diagram with the correction proposed in references [28, 31, 32] is in the lower part of Fig.14.

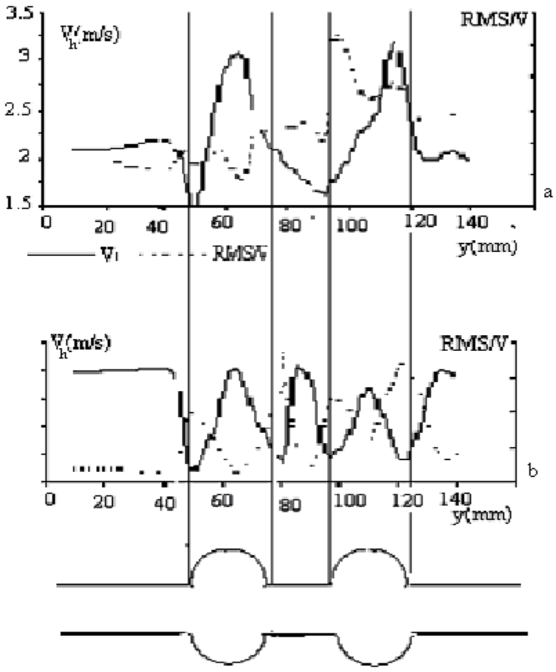


Figure 14. v_x distribution in the cylindrical tube with two spherical widening, without a) and with b) geometrical corrections [32]

Determination of Cp by LDA

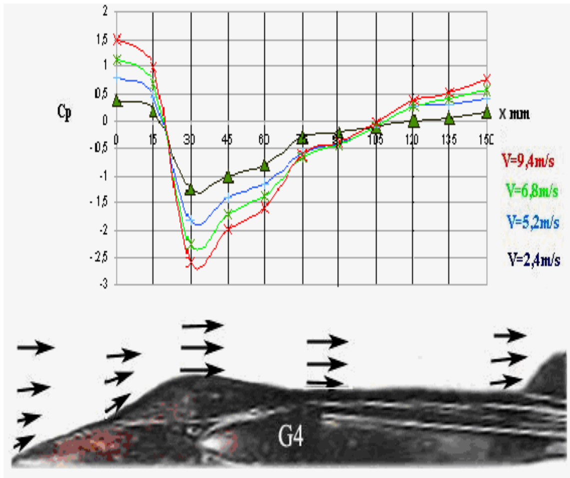
The flow velocity distribution around the G-4 airplane model has been measured by LDA in the T-33 water tunnel [23, 24]. The values of velocity are used for determination of the pressure coefficient distribution along the wing center span and along the pilot cabin. Some of the results are presented in Figures 15a and 15b. [32].

The measurement of vector velocity on the upper surface of the G4 wing model is made with purpose to detect the free stream velocity and the angle of attack when the cavitation has appeared on the cabin and the leading edge. An increase of V_∞, generally increases the local pressure coefficient and hence increases pressure gradients. This is analogous to shock wave appearance after supersonic flow in the air.

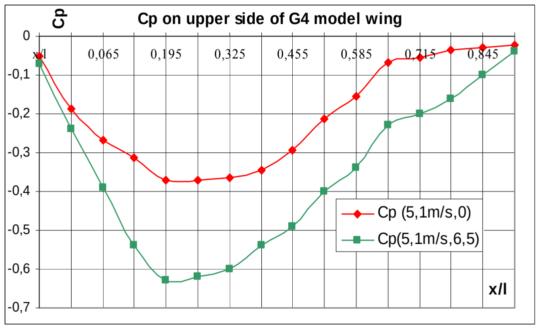
LDA measurement around hydrofoil

Two methods have been used to investigate the flow through a 2D straight profile grid (with three profiles), in the test carried out in the VTI water tunnel [33-36, 39, 40].

The flow visualization was performed using aniline dyes and air bubbles. They were injected in the flow at the distance of about 1m in front of the model, using a special device. Fig.16 shows the flow field visualized by air bubbles.



a)



b)

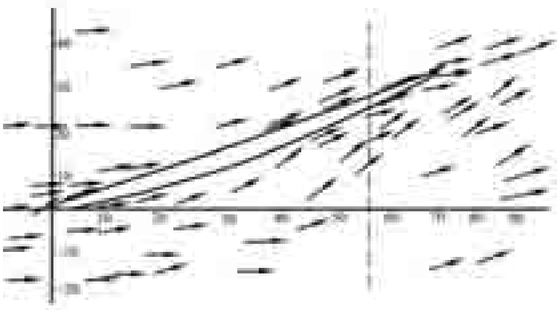
Figure 15.LDA Measurements in the water tunnel, (a) Velocity vector distribution around the pilot cabin and *Cp* determined from the LDA measurements for V_∞ = 2.4 to 9.4 m/s, (b) *Cp* for the G4 wing model $V\infty$=5.1 m/s, α=0° [23,24].

Figure 16. Flow visualization around hydrofoil by air bubbles for V_∞ = 3m/s [33, 40]

The velocity distribution around the central profile has been measured by 2D LDA.

The results of the 2D LDA measurements have been used as data for making the velocity vector diagrams shown in Fig.17a, and for definition of the boundary conditions in the numerical simulation by Fluent 6, 1.

Since the velocity vectors are the tangent lines of the streamlines, the vector diagram indirectly enables the flow visualization. Very useful was the LDA measured turbulence in the test section, before the model. Fig.17a shows velocity vectors around the hydrofoil for α=25°, V_∞=5,32m/s; a LDA measurement, 17b numerical simulated velocity vectors.



a)

b)

Figure 17. Velocity vectors around the hydrofoil for $V\infty$ = 5.32m/s, α = 25°, a) LDA measurement, b) numerical velocity vectors distribution.

Some examples of LDA technical applications

As it has been mention before, LDA is an ideal measurement technique for non-intrusive investigation of velocity and turbulence in gas or liquid flows. The applications described below (Figures 18 - 23) demonstrate the wide relevance of LDA across the spectrum of scientific and industrial research [6].

Figure 18. Investigation of the flow between the impeller blades of a pump (Grundfos A/S, Denmark) [6]

Figure 19. Investigation of aerodynamics of en external rear view car mirror (Daimler Chrysler, Germany) [6]

Figure 20. Measurements in an optical glass engine (Lotus Engineering [6])

Applications include: car body aerodynamics, airflow in passenger compartments, engine flow, aircraft or ship model testing, flow around helicopter rotors, airflow around buildings and other objects, turbulence research, industrial process flows, etc. In automotive testing, LDA is used both to obtain information on the global flow field and to study details such as air flow around mirrors (Fig.19) wheels and engine (Fig.20).

Fig.21 is an example of the LDA application for a flow measurement in a wind tunnel, Fig.22 in a basin, around a ship model [6] and Fig.23 for studding the flow inside a cyclone model.

Figure 21. Measurements by the 3D LDA around a model of a transport plane (Onera, France) [6]

The flow around a helicopter rotor can be studded by LDA. The synchronization of the angular position of the rotor blades and LDA measurements has to be made. The combination of LDA measurement and CFD methods is often used during the design and optimization phase in industrial processes.

Figure 22. LDA measurement around a ship model (University of Bristol) [6]

The overview of other techniques using Doppler effect for Flow measurement

Phase Doppler Anemometry or Particle Dynamics Analysis (PDA), is an extension of LDA. PDA systems measure on-line the size, velocity and concentration of droplets in gaseous flows [41, 42].

Figure 23. LDA used for studding the flow in a cyclone model, [6]

In an LDA system there is only one photo-detector, in PDA two (Fig.24). When the particle passes through the measuring volume, both photo detectors receive a Doppler burst of the same frequency, but the phases of two bursts vary with the angular position of the detectors. The phase difference between the two Doppler bursts depends on the size of the particle, provided that all other geometric parameters of the optics remain constant.

Figure 24. Components of a PDA system[41]

The planar PDA is used to resolve the 2π ambiguity and for validation. The Dual PDA has been developed especially to eliminate sizing errors due to trajectory and slit effects and thereby to increase the accuracy of mass flux and concentration measurements. The dual PDA uses four detectors.

Doppler Global Velocimetry (DGV)-also called Planar Doppler Velocimetry (PDV) [50] is a particle based velocity measurement technique giving the velocity of particles injected in the flow, as LDA.

The difference is that LDA determines the velocity at one point in space, while DGV has the capacity to give the velocity at a multitude of points in a given region of space [42].

The basic principle consists in determining directly the Doppler shift of the light scattered by a moving particle. In this technique a laser sheet is used to illuminate the flow, the illuminated region being imaged onto a video camera through a specially made absorption cell containing iodine. As the scattered laser light is shifted in frequency due to the Doppler effect, the transmission through the absorption cell will also change. This converts the frequency change into an intensity change which can be more readily detected.

Conclusion

In this article an attempt is made to describe the fundamental principles of LDA and to review some applications. LDA today has become a very useful tool used in the world-wide centers for scientific and industrial application. Advanced novel techniques for sophisticated LDA applications have been developed in the recent time, and performances of laser Doppler anemometers are significantly enhanced.

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Laser Doppler anemometrija i njena primena u aerotunelskim ispitivanjima

Zadnjih dvadesetak godina, laser Doppler anemometrija je veoma značajna tehnika za merenje brzine strujanja u aero i vodenom tunelu u VTI-u. U ovom radu je prikazan kratak pregled osnovnih teorijskih principa ove metode, napravljen je pregled različitih tipova anemometara i dati su primeri nekih primena laser Doppler anemometrije.

Ključne reči: **Laser Doppler anemometrija, brzina fluida, turbulencija, aerotunel, vodeni tunel.**

Anémométrie laser Doppler et son application dans les essais dans les souffleries aérodynamiques

Pendant les vingt dernières années, l'anémométrie laser Doppler est une technique très importante pour les mesurements de la vitesse du courant dans la soufflerie aérodynamique et dans le tunnel hydrodynamique de VTI, à Belgrade. Dans ce papier on a donné un bref aperçu des principes théoriques de base de cette méthode, description de différents types d'anémomètres et on a cité quelques exemples de l'application de l'anémométrie laser Doppler.

Mots clés: **anémométrie laser Doppler, vitesse du courant, turbulence, soufflerie aérodynamique, tunnel hydrodynamique.**