LASER DOPPLER VELOCIMETRY

BASIC PRINCIPLES .......................................................................................................................... 2
THEORY .............................................................................................................................................. 4
CASE STUDY 1: TURBULENT FLOW: PISTON-CYLINDER ASSEMBLIES .................................. 7
CASE STUDY 2: SUPERSONIC FLOWS ................................................................................................. 8
CASE STUDY 3: MEASUREMENTS IN TURBO-MACHINERY ......................................................... 11
Basic Principles

Consider the Michelson interferometer shown in Figure 1. The original input beam is divided in amplitude to give two beams at the beamsplitter. Each beam travels to a mirror where it is reflected and is recombined at the beamsplitter to give an output beam. If the total difference in path length for the two beam is equal to a an integer number of wavelengths we will get constructive interference and a bright spot at the output. If, however, the difference in the total distance travelled for the two beam is half a wavelength we will get destructive interference and the light waves will cancel to give a dark output. If we now move the mirror M2 towards or further from the beamsplitter by a distance $\lambda/2$, where $\lambda$ is the wavelength of the light, the output will change from dark to bright to dark again as we change the path difference between the beams. It is important to note that if the path difference between the beams is larger than the coherence length of the light no interference will be seen.

![Figure 1: The Michelson Interferometer](image)

If the mirror M2 of the Michelson interferometer is moved continuously along its optic axis at velocity $v$, then the interference fringes move across the plane of observation at a frequency $f = 2v/\lambda$. The output of a photodetector placed in this plane will vary at frequency $f$ and $v$ can be determined if $\lambda$ is known.

This result can be interpreted from the rate of change of the separation between mirror M1 and the image M2' in terms of half-wavelengths. Alternatively, we may regard M2 as a moving source of waves, that is, the light reflected from it will undergo a Doppler frequency shift given by

$$v' = v \left(1 \pm \frac{2v}{c}\right)$$

relative to the light reflected from the stationary mirror M1. (As far as an observer is concerned the velocity of M2', the image of M2 in the beam-splitter M, appears to move at velocity 2v when the actual velocity of M2 is v). Thus when the light waves reflected from the two plane mirrors are mixed beats waves will be formed of frequency $f = v - v' = 2vv/c$ or $f = 2v/\lambda$ as before. This then is the basis of laser Doppler velocimetry (LDV).
Example

Let us calculate the frequency shift in the 632.8 nm He-Ne laser line reflected from a car travelling at 20 ms\(^{-1}\). We have:

\[
f = v - v' = \frac{2vv}{c} = \frac{2v}{\lambda} = \frac{2 \times 20 \text{ms}^{-1}}{632.8 \times 10^{-9} \text{m}} = 6.32 \times 10^7 \text{Hz}
\]

Note that this is about 1 part in 10\(^7\) of the frequency of the laser output. Clearly the laser must be stabilised so that the frequency drift is much less than this.

In practice the moving mirror could be replaced by any surface or even by impurity particles such as specks of dust, algae or air bubbles in gaseous or liquid flows. The impurities act as scattering particles and their mean velocity which, if the particles are small enough, is the same as the velocity of the fluid and is given by the mean Doppler shift (\(v - v'\)) of the receiver signal.

The technique has the great advantage of being non-invasive and although it was used before the development of lasers, the highly coherent output of lasers has made possible the development of almost ideal Doppler velocimeters. These require no calibration and give a reading which is linear with velocity in liquids and gases. Simultaneous measurements of turbulence and flow pulsations are also possible with good accuracy. Note that LDV relates to the measurement of any fluid but, when referring to air flow measurements, it is common to use the term laser Doppler anemometry (LDA).

The first use of LDV was reported in 1966. The method developed, which is often called the reference-beam technique and is illustrated in Figure 2 below, suffers from a poor signal-to-noise ratio and sensitive alignment has to be achieved and maintained. The position of the photodetector (and hence the reference-beam detector) determines the component of velocity measured. These disadvantages have been overcome with the development of the dual-beam technique shown in Figure 3. In this arrangement two beams of equal irradiance are focused by a lens into the fluid flow whose velocity is to be measured; the region where the beams cross becomes the measurement region.

Figure 2: The Reference Beam Technique
Figure 3: The Forward Scattering Technique

**Theory**

When a particle (present in a fluid for example) passes through the measurement region it scatters light from each beam. The light has its frequency shifted so that when the two scattered beams are mixed or heterodyned a suitable detector will see only the difference frequency $\Delta \nu$. If $k_1$ and $k_2$ are unit vectors in the directions of the incident beams, $k_s$ is a ray of scattered light and $v$ is the particle velocity (see Figure 4) then the frequency shift of the first beam is given by:

$$v_1' = v \left(1 + \nu \cdot \frac{k_s - k_1}{c}\right)$$

or, assuming $v \ll c$,

$$\Delta v_1' = \nu \cdot \frac{k_s - k_1}{\lambda}$$

Similarly

$$\Delta v_2' = \nu \cdot \frac{k_s - k_2}{\lambda}$$

The beat frequency from mixing the two scattered beams is then

$$\Delta v = \Delta v_1' - \Delta v_2' = \nu \cdot \frac{k_s - k_1}{\lambda}$$

$$\Delta v = \frac{1}{\lambda} \nu \cdot (k_s - k_1)$$

$$\Delta v = \frac{1}{\lambda} |\nu| |k_s - k_1| \cos \phi$$

We see that the component of velocity measured is always in the direction $(k_s - k_1)$, that is, normal to the bisector of the beams, independent of the direction of viewing. In general this allows us to use a large collection aperture and results in good signal quality.
If $\theta$ is the angle between the beams, then

$$\Delta v = \frac{2v}{\lambda} \cos \phi \sin \frac{\theta}{2}$$

since $|k_1| = |k_2| = 1$ and from Figure 4, $|k_1 - k_2| = 2\sin (\theta/2)$

An alternative explanation of the dual-beam method is as follows. If the two incident beams are coherent, then their intersection will result in the formation of a set of interference fringes in the plane of the beams at the crossing point (see Figure 5). The fringes will be parallel to the bisector of the beams, that is, normal to the direction of the component of flow being measured. A particle passing through the alternate bright and dark bands will scatter light whose irradiance will vary, the rate of variation being proportional to the particle velocity.

The fringe separation $d$ is given by:

$$d = \frac{\lambda}{2 \sin(\theta/2)}$$

The particle velocity is given by $v = df$, where $f$ is the frequency of the photodetector output signal; $f$ is the same as the Doppler frequency so that

$$v = d \Delta v = \frac{\lambda}{2 \sin(\theta/2)} \Delta v$$

as given in the previously derived equation above, with $\phi = 0$. 

Figure 4 : Geometry of the Scattering Vectors
A typical dual-beam optical system is shown in Figure 3; the lenses, beam-splitting prism and photodetector (a photomultiplier or pin photodiode can be used) are mounted on an optical bench. This system is referred to as the forward-scatter arrangement and provides the best signal quality, but obviously requires optical access to the flow in two directions. Conversely, in the case of backscatter arrangements all the optics are on one side of the flow but the signal irradiance is much less than in the forward scatter arrangement. The lenses $L_1$ and $L_2$ can be linked together so as to share a common focus. Then by moving them as a unit the fluid flow can be traversed and the velocity profile determined.

Light from a low-power (-5 mW) HeNe laser passes through a beam splitter which gives two parallel beams of similar power. The direct beams are prevented from reaching the photodetector by the aperture $A$, so that only the scattered light is focused onto the detector by lens $L_3$. This enhances the signal-to-noise ratio and prevents the relatively high power of the direct beams from causing fatigue in the photocathode.

The output from the photodetector is fed to a spectrum analyser whose output is recorded on a storage oscilloscope or chart recorder. The detector cannot respond directly to signals at the frequency of visible light and the alternating signal in the detector output consists of difference terms of the form indicated by equations above. The record consists of an approximately Gaussian-shaped curve centred on the Doppler frequency. The spread in the width of the peak is due to instrumental effects and possibly velocity fluctuations. Finding the velocity necessitates estimating the centre of the peak, which can be done to an accuracy of about 1%. This can be improved by more sophisticated signal-processing techniques.

The applications of LDV are many and varied; the technique has been used for measurements in wind tunnels, internal combustion engines, near flames, of the velocity of moving parts of machinery, propellers and the like. It has also been used for the measurement of the velocity of blood flow; indeed the dynamic range extends from micrometers per second to several times the speed of sound.

Although for many applications HeNe lasers are ideal, in backscatter configurations where more power is required argon lasers with output of a few watts have been used. The argon laser has two strong wavelengths which can conveniently be used for measurements of two flow components.

Since the scattering efficiency increases as the wavelength decreases, HeCd lasers ($\lambda = 446$ nm) may be used instead of the red line of HeNe lasers if they become more cost effective or alternatively the green line ($\lambda = 543.5$ nm) of HeNe may be used. Measurements at large distances approaching a kilometre or so have been made in the atmosphere using CO$_2$ lasers. In this case the reference-beam mode is used to measure the velocity along the optic axis.
Case Study 1: Turbulent Flow: Piston-Cylinder Assemblies

Knowledge of the flow patterns within piston cylinder assemblies, with and without combustion, is important to the understanding of the influence of variables such as valve geometry and lift, port geometry and location, and piston-crown slope. Investigations have been carried out by flow visualisation and by hot-wire anemometry and, recently, by laser-Doppler anemometry which offers the possibility of measurements in both non-combusting and combusting systems within the limitations imposed by optical access and particle presence.

Detailed investigations in the isothermal flow in piston-cylinder arrangements with open valves have been reported. They are intended to provide new information of direct relevance to, and at the same time to aid the development of, calculation methods. Two types of piston-cylinder assembly have been used. A small number of measurements have been obtained in a single-cylinder Petter Diesel engine using a small window in the cylinder head to provide optical access. A much larger number of more precise measurements have been obtained from a piston-cylinder assembly fabricated from perspex and allowing ready optical access through the cylinder wall. Further details of the former are provided below; the perspex assembly, and related instrumentation, are described below.

The optical arrangement used to obtain measurements in a single-cylinder Petter Diesel engine, motored at 550 rpm, is shown in Figure 6. The injector was removed and replaced by a 31.75 mm diameter sapphire window, but the limited optical access can readily be appreciated and is a typical, or perhaps a favourable, representation of what may be expected in other configurations. The optical system operates with backward-scattered light and is hampered, at some piston positions, by flare. The non-combusting flow was seeded with atomised silicone oil, drawn from a flexible reservoir through the intake valve and expelled through the exhaust valve. The data rates associated with this arrangement were of the order of 10/s with signal-to-noise ratios greater than 5 and it is clear that quantitative results require an inconveniently long period of time.

Faster data rates can be obtained in several ways. A greater rate of addition of seeding particles, for example, has this result but in many cases only for a short period of time before window contamination rapidly lowers the signal quality. An improved optical arrangement, for example with a greater magnification, can help appreciably. Faster data rates may be obtained by photon correlation methods but results so far are far from conclusive and the special problems of flare from the piston head may limit the range of applicability of this technique. A modified optical arrangement has been used and has resulted in detailed measurements in the Petter engine, with and without compression. Results can, however, be obtained very much more easily in purpose-built arrangements.
Figure 7: Streamlines in a Piston-Cylinder Assembly

Figure 7 shows streamlines obtained in a perspex cylinder, with an open-valve geometry as shown, and a piston which is driven in simple harmonic motion by a crank rotating at 200 rpm. The 75 mm diameter perspex cylinder allowed the use of a forward scatter optical system with a 5 mW He-Ne laser and frequency shifting by a rotating diffraction grating. The optical arrangement could be traversed across the horizontal diameters and parallel to the cylinder axis. The curvature and thickness of the cylinder wall imposed limitations on the regions of the flow accessible for measurement: these were of no importance in axisymmetric flows and of small importance for fully three-dimensional flows. As a consequence of the optical access and the use of forward scattered light, the signal quality and data rates were excellent and allowed measurements with considerably improved accuracy and smaller investment of time, money and equipment, than those shown above.

Case Study 2: Supersonic Flows

Figure 8: Comparison of LDA and Pitot Methods for Supersonic Flows

Figure 8 and Figure 9 are concerned with measurements obtained in supersonic flows. The major attraction of applying laser-Doppler anemometry to supersonic flows is that there is no need for a probe to be inserted into the flow. On the other hand, it is necessary to have particles which scatter light and, with the significantly higher turbulence frequencies involved, more difficulties may be anticipated in ensuring the presence of particles which follow the flow to satisfactorily high frequencies.

In an early paper, workers demonstrated that laser-Doppler anemometer provided measurements in the range from 150 to 600 m/s which agreed with those from a Pitot tube to within the precision expected of Pitot tubes. In common with most supersonic flow measurements, a high power argon laser (in this case 300 mW) was employed. A reference-beam system was used along with a Fabry-Perot etalon for signal
processing. The measurements were obtained in a jet flow. Subsequent to these measurements, and using ice particles in a Mach 1 jet, the results of a Pitot tube with those from a laser-Doppler anemometer were again compared and it was again confirmed that both instruments gave closely similar results across a profile: in addition to the mean velocity results, measurements of the RMS longitudinal velocity fluctuations were reported. These results are in Figure 9 and clearly demonstrate scatter, a centre line value which is unexpectedly low and a maximum value which is unexpectedly high. The precision of the Fabry-Perot, as used for this experiment, requires more detailed quantification, particularly since the mean velocities are significantly less than Mach 1. The question of the ability of the ice particles to follow the flow is also questionable and is discussed below.

![Figure 9: LDA Results for Supersonic Flow](image)

Measurements of mean velocity obtained through an oblique shock wave generated on a 10° cone have been reported and are shown in Figure 9. The free stream Mach number was 2.9. The measurements were obtained using an argon laser, a reference-beam optical arrangement with small angle to minimise the Doppler frequency and signal processing by frequency analysis. The air flow was seeded with a water-oil aerosol and resulted in measurements which indicated substantial smearing of the shock wave. It was concluded from this that the aerosol particles were too large to follow the flow satisfactorily and, subsequently, use of DOP droplets, atomised with a nozzle, was made with the larger particles removed by baffles.

More recent measurements obtained in a small wind tunnel using a 1 W argon laser, fringe mode optics with in-line light collection and dust particles present in the atmosphere to scatter light: a frequency analyser was used to process the signals. The size distribution of these particles had a maximum at 0.16µm and that half of all particles were smaller than 0.28µm in diameter. These results were obtained from measurements with an electron microscope. Previous efforts showed that similar particles were able to follow velocity discontinuities of 200 m/s within less than 4µs. It would seem, therefore, that the dust particles should follow the velocity through a shock wave with satisfactory resolution. This may be judged from Figure 10.

As can be seen from Figure 10, measurements were conducted through an oblique shock wave generated by a 15° wedge. The results demonstrate that the measured velocity ahead of the shock wave is in agreement with calculations to within 1%. The measurements downstream of the shock wave are in less good agreement but this may be due to the shock wave itself. The particles were able to react to a sudden velocity variation of the gas flow within less than 1.5 mm and, since the diameter of the observation volume in a direction of the velocity vector was approximately 0.8 mm, the particles followed the flow with satisfactory resolution.
Similar measurements have been made through the normal shock wave in the upstream region of a jet flow. In this jet, ice particles, dust and oil droplets contributed to the scattered light signal and the response distance of the particles across the normal shock was observed to vary from approximately 0.1 mm to 0.3 mm. These response distances are once again small compared to the control-volume dimensions.

A series of measurements have been obtained at the NASA, Ames Research Centre in a 2 ft transonic tunnel and in an 8 in. supersonic tunnel. Figure 11 illustrates the instrumentation used in the 8 in. tunnel to obtain measurements concerned with the flow in and around the region of boundary layer separation caused by a generator induced shock wave. As indicated, the free-stream Mach number was 2.9 with a corresponding unit Reynolds number of $5.7 \times 10^7 \text{ m}^{-1}$.

Preliminary measurements were performed in the unseeded flow and in the flow seeded with latex pigment particles of nominal diameter 0.5 µm and atomised in a water solution. The particle response, observed in the same manner as that of the previous two figures, showed similar results with response distances in the two cases of around 15 mm and 5 mm respectively. The seeded flow was used for subsequent measurements in the knowledge that, in the lower velocities of the boundary layer and separation region, the nominal relaxation distance would be of order 2 mm with corresponding frequency response up to around 50 kHz. The data rate, in the seeded flow, ranged from 100 to 500/s.

A similar laser-Doppler anemometer, but utilising two wavelengths to determine two velocity components, has been used to measure in the transonic flow close to the surface of an axisymmetric model located in the 2 ft tunnel. With Bragg-cell frequency shifting, and the two-colour systems, simultaneous measurements of two orthogonal velocity components were obtained without the need for ±45 degree fringe orientations. As in the system indicated above, light was collected in an off-axis forward direction. The measurements were
obtained, through optical-glass windows, at a free stream Mach number of 0.875 and with a unit Reynolds number of $13.6 \times 10^6 \text{m}^{-1}$ and included values of longitudinal velocity and the corresponding intensity, flow angle, and Reynolds shear stress.

**Case Study 3: Measurements in Turbo-Machinery**

Laser-Doppler anemometry has been used by several turbo-machinery manufacturers and research organisations with a view to design improvements, particularly in compressors. The first such reported experiment concerned with measurements of the magnitude and direction of the mean velocity in the blade passages of the first stage of a two-stage, low-speed axial compressor. The rotor had 55 blades with a tip diameter of 60\textprime and a hub-to-tip radius ratio of 0.5; the measurements were obtained at an average rotor speed of 590 rpm. A pulsed argon laser, with a peak power of 6 W for $25\mu\text{s}$, was used to provide the light beams, and, to ensure that measurements were made at a required location within a specified blade passage, the laser pulses were synchronised with the rotor blades. The laser, transmission/collection optical arrangement and photomultiplier were secured to a frame: the collection of back-scattered light allowed the integration of the optical components into a single, robust unit. Optical access to the blade passages was provided by an antireflection coated window. The beam angle of the transmission optics was $2^\circ$ and a $10^\circ$ cone of back-scattered light was collected.

The flow to the compressor was locally seeded, by spray-atomising a dilute water suspension of 1mm diameter polystyrene latex particles into the air entering the compressor. Since the flow velocities were of the order of 100 ft/s, the particles, even allowing for severe agglomeration, would follow the flow with a resolution which would permit mean velocity measurements to a precision considerably greater than was made possible by the instrumentation.

![Figure 12 : LDA Measurements Near Rotor](image)

Experiments were carried out to demonstrate that measurements obtained from the laser-Doppler anemometer system agreed with those from a hot-film anemometer and a pitot-static probe in turbo-machinery applications. A second objective was to obtain measurements where the conventional probes could not be used. The comparisons were made in the inlet plane of the rotor and revealed that the three forms of instrumentation provided mean velocity values which were generally within 2-3\% of each other; these tests were carried out with three throttle settings including a near stall condition and encompassed radial locations corresponding to 50\% of the distance from hub to tip.

A sample of the measurements obtained within the rotor passage at the mid-chord position is indicated in Figure 12; these measurements could not have been obtained with the conventional probes. The blade shadow corresponds to a region of flow which could not be penetrated by the light beams because of the blade shape. The measurements reproduced in the figure correspond to the near stall condition. The
stagnation regions can readily be identified. The complex flow patterns in the first half of the blade passage are significantly different from those obtained from potential-flow calculations and allow boundary-layer calculations to be undertaken with greater confidence. It should be noted that the region of measurement does not include the boundary-layers.

The optical and counting arrangements used for the above measurements were improved to allow the measurement of turbulence energy spectra. The measurements were extended to a smaller fan with 30 blades, a tip radius of 559 mm and a rotational speed of around 19,000 rpm. Under such conditions, transonic relative velocities and absolute velocities exceeding 250 m/s are encountered. Severe requirements are then imposed on the ability of the seeding particles to follow the flow.

Measurements of mean velocity in similar geometries have been reported in the transonic fan of an aero engine, and in a transonic axial compressor. These experiments kept the Doppler frequencies below about 20 MHz, even at the high velocities in question, by using a small beam intersection angle (fringe spacings between 10 and 18\(\mu\)m). Consequently long measuring volumes, aligned along a radius of the compressor, could be accepted because of the relatively large dimensions of the machines. A two-component optical system with back-scatter light collection was used; signal processing was accomplished with commercial period timing counters whose analogue outputs were recorded for further analysis on tape.

Measurements in the vicinity of a model helicopter rotor are also relevant to the application of laser-Doppler anemometry in the unsteady flows of rotating machines.

![Transit Anemometer used with LDA](image)

Measurements by laser-Doppler anemometry in centrifugal compressors have been reported. All these tests have been made in compressors where high rotational speeds, high absolute gas velocities, and small passage dimensions particularly in the diffuser pose severe problems. The ranges of rotational speeds, maximum velocities and minimum dimensions in these measurements were 11,800 to 60,000 rpm, 4·5 to 350 m/s, and 3.2 to 17.5 mm respectively. These conditions force a compromise between good spatial resolution obtained by increasing the beam intersection angle, and a low ratio of Doppler frequency to velocity obtained by decreasing the angle.

Because of these difficulties, two spot (transit) anemometers are often favoured in turbo-machinery. Thus a “laser 2 focus” anemometer specifically for this application has been developed as shown in Figure 13. In this arrangement the two incident light beams are focused to point foci and the velocity is deduced from the transit time of particles crossing both foci. The intensity of each of the spots can be made 100 times greater than that of the fringes of a dual beam anemometer, giving potential advantages where background light levels are high. It has been argued that flare rejection and spatial resolution are better with a two-spot arrangement, so that measurements are easier obtained close to windows and walls, where optical access is limited, and in flows of small dimensions. The approach has the related disadvantage that measurements are required with more than one orientation of the spots, and are thereby limited to turbulence intensities.
below about 30%. It has, however, been employed successfully in centrifugal compressors and in axial compressors and is being further developed for turbo-machinery studies.