Velocity Measurement using Laser Doppler Velocimeter

Introduction

Measurement of instantaneous point velocities in water is of very importance in two types of studies in hydraulics viz. (i) boundary layer studies, in which point velocities are measured close to a solid boundary and, (ii) turbulence studies, in which the random fluctuations of velocity at a point are to be measured.

Only two types of instrument are used for the measurement of instantaneous point velocities in such fields: (i) Hot film anemometer; and (ii) Laser Doppler velocimeter. The Hot film anemometer represents a complicated technique of measurement, which often gives erroneous results as the measurement is affected by changes in ambient temperature, turbidity of water etc. For this reason, the simple and more reliable technique represented by the Laser Doppler velocimeter is generally used.

The Laser Doppler velocimeter represents a unique no-probe technique of measuring the instantaneous point velocities in a fluid flow. It was developed around the year 1968 as a result of research work carried out by the National Aeronautics and Space Administration, U.S.A. The instrument in the Hydraulic and Water Resource Engineering Laboratory IIT Madras was locally built in 1974 by Jayaraman and later on it was modified in 1995 – 1997.

Principle of the Instrument

The instrument measures the velocity at a point in the fluid, flowing in a glass walled conduit or channel, by detecting the Doppler shift in the frequency of the scattered light originating from minute suspended particles in the flow that happen to cross the point of measurement defined by two intersecting laser beams. The laser source is used as it gives a narrow, intense and truly parallel (i.e. highly collimated) light beam of high spectral purity (i.e. very low spectral bandwidth).

The salient features of this instrument are

(i) No physical probe is required, to obstruct the flow.

(ii) Excellent spatial resolution, (the measuring volume is of the order of 0.02 mm^3)

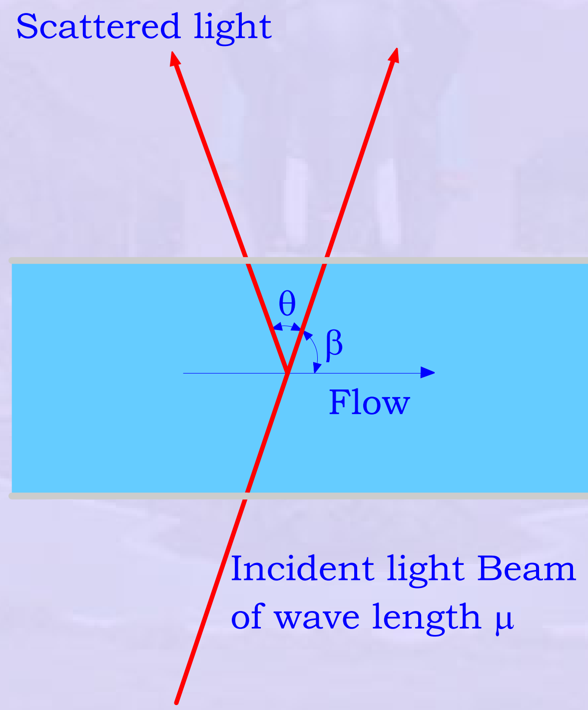
(iii) No transfer function is involved, the output voltage is linearly related to the Doppler frequency which in turn, is linearly related to flow velocity.

(iv) Very fast response to fluctuating velocities, the typical frequency response going upto 50 kHz for a Doppler frequency of 1 MHz.

(v) Can be used in both gas and liquid flows.

Theory of Measurement

Consider a light beam of wavelength μ crossing a flow stream at an angle β with direction of flow (Figure). When illuminated by the light beam suspended particles in the flow will scatter light in all directions. This scattered behaves as though it originated from moving particles, and hence is Doppler-shifted with reference to the frequency of the incident light.



LIGHT SCATTERING

It can be shown that if the scattered light is picked up at an angle θ with the direction of the incident light beam, the Doppler shift f_D is given by $f_D = \frac{v}{\mu}\left[\left(\cos\theta - 1\right)\cos\beta - \sin\theta \sin\beta\right]$

in which v is the flow velocity. It may be noted that when $\theta = 0, f_D = 0$. For small values of (i.e., less than 10 degrees), increases as increases.

If the incident and scattered beams are equally inclined to a normal to the flow direction, $\beta = \left(90^o - \frac{\theta}{2}\right)$

then

$$f_D = \frac{v}{\mu}\, 2\sin\frac{\theta}{2}$$

If the Doppler shift f_D of the scattered light is known than the velocity may be expressed as $v = f_D \frac{\mu}{2\sin\frac{\theta}{2}}$

The laser used for this application is a Helium - Neon laser, giving out a red light beam for which $\mu = 0.6328$ micron. Expressing in m/s and f in MHz.

$$v = \frac{f_D * 10^6 \left(0.6328 * 10^{-6}\right)}{2\sin\frac{\theta}{2}} = \frac{0.3164\, f_D}{\sin\frac{\theta}{2}}$$

i.e., $v = C_0 f_D$

in which, $C_0 = \frac{0.3164}{\sin\frac{\theta}{2}}$

C_0 can be made an integer by adjusting the beam inclination θ to an appropriate value as indicated in table 1.

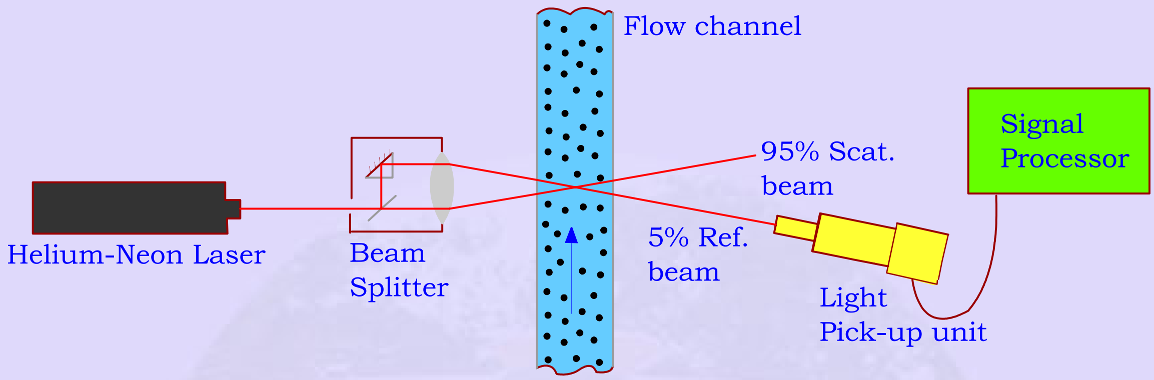
Table 1

θ in degrees	7.25	4.53	3.63	3.02	2.42	2.01	1.81
C_0	5	8	10	12	15	18	20

The beam angle θ can be adjusted by allowing the beams to strike a wall at distance S of about 4 m (measured from the point of intersection of the beams), and adjusting the beam angle control screw in the beam splitter so that the centre to centre distance between the beam spots on the wall equals $2s\tan(\theta/2)$. In the case of a liquid flow θ, should be reckoned in air, before the beams enter the channel.

Instrumental set-up

The instrument can be set up in either of two modes of measurements, namely, the Reference beam mode and the interference fringe mode. Fig. 2 shows the set-up in the reference beam mode.



SET-UP IN REFERENCE BEAM MODE

The instrument has four components

(i) Laser source Helium-neon, (ii) Beam splitter; (iii) Light pick-up unit; and (iv) Signal processor. By means of a Beam splitter the light from a 2 mill watt Helium-Neon laser is split up into a strong (95% power) scattering beam and a weak (5% power) reference beam. The beam inclination θ could be raised using adjustment scale (provided in beam splitter) and also the intensity of reference beam could be attenuated by means of a lens in the beam splitter. The two beams, which are kept equally inclined to the flow direction, are made to intersect at the point of velocity measurement in the channel. When illuminated by the strong scattered beam minute suspended particles in the flow scatter light in all directions. The optimum range of size of scattering particles is 0.5 to 5 microns. Too fine particles will lead to Brownian motion, whereas too large particles will increase the system noise by excessive masking of the light picked up. Ordinary tap water contains adequate fine suspended particles to provide enough scattering. The presence of large particles, (which is not desirable) in water is indicated by the intermittent glittering of the laser beam. The light scattered by suspended particles in Doppler-shifted. The magnitude of the shift depends on the direction in which it is picked up. On the other side of the channel, the light pick-up unit is so positioned, and its telescope so focused, that it picks up the reference beam as well as scattered light in the same direction originating from the point of intersection of the two beams. The light is focused on to a tiny electronic device called P.I.N. photodiode, where optical mixing takes place and a weak electrical signal, (the Doppler signal) emerges, having a frequency equal to the Doppler shift. The Light pick-up unit contains a built-in preamplifier to boost the Doppler signal to a more appropriate level for transmission to the Signal processor unit. In the Signal processor unit, the Doppler signal is first passed through one of a set of three sharp band-pass filters to reduce the noise content of the Doppler signal. It is then further amplified. The frequency of the Doppler signal is then converted to a proportional voltage by an f-V converter. The converter has fast response which enables it to track closely the Doppler frequency. The instantaneous output voltage can be recorded on a strip chart recorder or can be digitized and stored on a floppy disk or Compact disc. The mean voltage, averaged over a few seconds, is indicated by a panel meter. The signal processor has 6 frequency ranges.

Band	Full scale MHz	Optimum range of measurement MHz
1	0.02	0.008 - 0.018
2	0.05	0.018 - 0.040
3	0.10	0.040 - 0.080
4	0.20	0.080 - 0.180
5	0.50	0.180 - 0.400
6	1.00	0.400 - 0.800

Experimental Procedure

1. The light output of the 2 mill watt Helium - Neon laser is to be examined before commencing the experiment. It is not dangerous to intercept the beam by the hand. However, one should not look directly into the laser source.

2. The laser and beam splitter are placed on an optical bench. The laser is placed on its platform and adjusted so that the beam is parallel to the optical bench and strikes the pin-hole of the beam splitter centrally.

3. Usually the beam angle control screw is present. Hence, the value of C_0 for which the beam inclination θ has been set is to be noted.

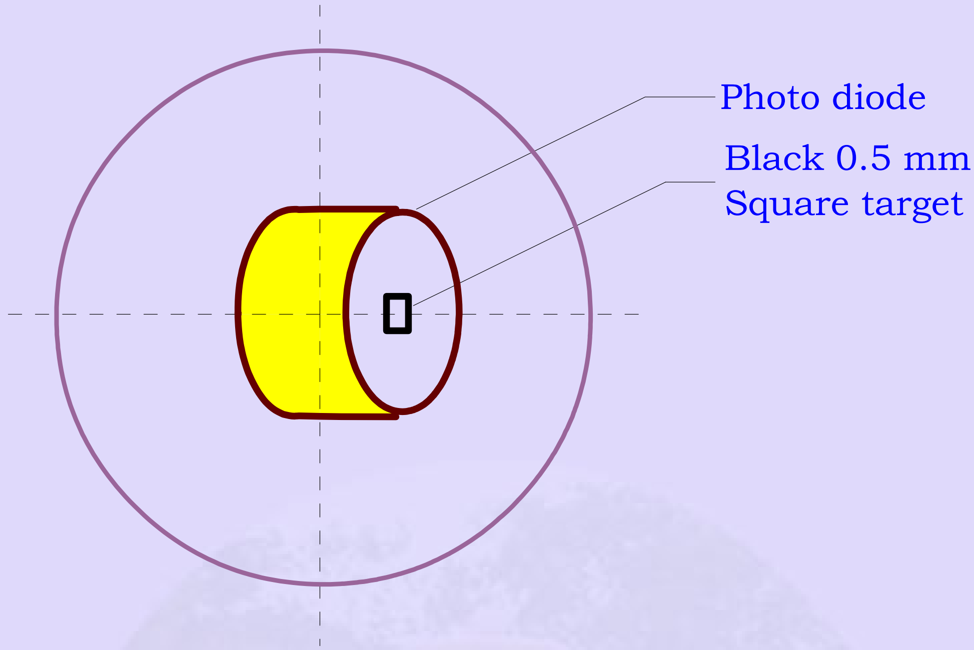
4. The reference beam attenuator screw should be turned sufficiently anticlockwise direction, and the emerging scattering beam and the unattenuated reference beam are to be observed.

5. The pump is started and the flow in the glass-walled channel is adjusted to the desired depth.

6. The optical bench is moved slowly so that the beams emerging from the beam splitter are equally inclined to the flow direction and intersect at the desired point of measurement of velocity in the channel.

7. It is to be noted that the light pick-up unit which is mounted on another optical bench is on the other side of the channel. It features: (i) A telescope with sliding inner tube for focusing; (ii) A six position shutter providing apertures of 0, 1, 1.4, 2, 2.8 and 4 mm diameter; (iii) A microscope to examine the photodiode; and (iv) A built-in preamplifier for boosting the weak Doppler signal.

8. The shutter opening is to be adjusted at 1 mm. The optical bench and light pick-up unit are so positioned so that (i) its shutter end is roughly 150 to 200 mm from the point of velocity measurement; and (ii) the reference beam enters the pin hole. Without moving the unit, the shutter size is increased to 4 mm. The reference beam position is to be checked through the microscope. It should fall on the target, in which case the black target will be recognizable in relief.



VIEW THROUGH THE MICROSCOPE

9. If the reference beam falls away from the target, the light pick-up unit has to be realigned. The shutter is readjusted to 1 mm. After leveling the optical bench it is moved in the appropriate direction, till the requirements 8(i) and 8(ii) are satisfied the shutter opening is increased to 4 mm again. The alignment of the reference beam is checked. It is to be noted that the black target will appear black even when the reference beam falls on it.

10. The steps 8 and 9 are repeated till the alignment is perfect. Finally the aperture is to be set to 2 mm.

11. From frequency band (1 to 6) of the signal processor, the band is appropriately selected to suit the expected Doppler frequency corresponding to the prevailing velocity of flow.

12. The gain control is advanced clockwise to about 75%. The signal drop-out warning light should get extinguished, indicating that the Doppler signal is being picked up. The meter may show some reading.

13. The reference beam is slowly attenuated by rotating the attenuator screw in the beam splitter in the clockwise direction. The meter reading will start increasing. The

screw is slowly and carefully adjusted so that the meter reading reaches a maximum. The signal drop-out warning light remains extinguished, except for occasional flashing.

14. The meter reading should lie between 30% and 90% of full scale. If not the band must be changed.

15. The Doppler frequency in MHz is to be noted then, Mean velocity of flow (m/s) $= C_0 f_D$ (MHz).

16. The tape output terminal to a strip-chart recorder to record the instantaneous velocity fluctuations resulting from turbulence. An output voltage of + 15 V corresponds to the full-scale Doppler frequency.

17. After the completion of the experiment the shutter of the light pick-up unit must be closed and the reference beam attenuator screw to be withdrawn. Then the signal processor, the laser and the pump are switched off.

At any cross section of the channel flow,

1. The velocity distribution in the vertical section and in the transverse direction could be obtained.

2. The discharge from the velocity distribution can be computed. Turbulence level can also be obtained.