Module 8

Lectures 40 to 42

Flow Visualisation

Keywords: Tracer methods, schlieren, colour schlieren, shadowgraph, interferometer, density gradients.

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8.1 Introduction

The visualisation of complex flows has played a uniquely important role in the improvement of our understanding of fluid dynamic phenomena. Flow visualisation has been used to verify existing physical principles and has led to the discovery of numerous flow phenomena. In addition to obtaining qualitative global pictures of the flow the possibility of acquiring quantitative measurements without introducing probes that invariably disturb the flow has provided the necessary incentive for development of a large number of visualisation techniques. The methods usually depend either on

(i) the reflection or scattering of light by small solid or liquid particles introduced into the stream or

(ii) on the natural changes of refractive index which accompany the density changes of a compressible fluid.

8.2 Flow visualisation by direct injection (Tracer Methods)

In this group of methods, small particles of solid or liquid are introduced into the fluid stream and observed by reflected or scattered light. It is necessary that such particles are of sufficiently small inertia to follow the local direction of fluid motion and sufficiently light as not to be sensibly influenced by gravity. Smoke or other particles in air and dye or other particles in water provide the necessary contamination for flow visualisation. Many substances have been used to visualise the flow of air and water. Smoke, helium bubbles, dust particles and even glowing iron particles have been used in air. A variety of dyes, particles, neutrally buoyant spheres and both air and helium bubbles have been employed in water.

Smokes consist of suspension of small solid or liquid particles in a transparent gas and are usually observed by the scattering and reflection of light by these particles. The word “smoke” used in flow visualisation includes a variety of smoke like materials such as vapours, fumes and mists.
A large number of materials have been used to generate smoke eg, the combustion of tobacco, rotten wood and straw the products of reaction of various chemical substances such as titanium tetrachloride and water vapour. The smokelike materials are referred to as aerosols (since aerosols are composed of collided particles suspended in a gas).

Two very practical points must be examined before the choice of smokelike material. The particles must be as small as possible so that they will closely follow the flow pattern being studied. The particles must be large enough to scatter a sufficient amount of light. Sizes below 1 μm but above 0.15 μm are good for scattering sufficient light and hence for photographing.

The most popular agent for airflow visualisation in wind tunnels has been smoke. The use of smoke requires a low turbulence level to minimize diffusion. Furthermore the smoke particles are so small that they cannot be observed or photographed individually. A larger neutrally buoyant tracer agent is needed to follow the paths of individual particles and bubble methods are useful in this regard.

The soap bubble is an ideal particle because its size and buoyancy can be controlled. The system for bubble method consists of a bubble generator, lighting and optical components and photographic equipments to record the paths of bubbles. Neutral buoyancy is achieved by filling the bubbles with helium. Bubbles from approximately 1 to 5 mm dia can be generated at rates up to 500/sec.
8.3 Index of refraction methods

The three methods included in this category are Schlieren, Shadowgraph and Interferometric techniques. Although all three methods depend on variation of index of refraction in a transparent medium and the resulting effects on a light beam passing through the test region quite different quantities are measured with each one. All three methods are used to study density fields in transparent media.

Density is a variable in compressible fluid. Particles added in incompressible fluids for visualising flows cannot respond to the thermodynamic changes. Hence, refractive index based methods are used for visualisation of such flows.

These methods are integral. They integrate the quantity measured over the length of the light beam. So, they are suited for two dimensional flow fields where there are no density variation in the field along the light beam except at entrance and exit of test section.

8.3.1 Theoretical background

According to Gladstone – Dale formula

\[ n - 1 = K \rho \]

where, \( n \) is the refractive index.

K values are (to a large extent).

constant for a wavelength. Varies slightly with \( \lambda \).

<table>
<thead>
<tr>
<th>Gas</th>
<th>K (cm³/gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>0.229</td>
</tr>
<tr>
<td>O₂</td>
<td>0.190</td>
</tr>
<tr>
<td>N₂</td>
<td>0.238</td>
</tr>
<tr>
<td>He</td>
<td>0.196</td>
</tr>
</tbody>
</table>
\( \rho \) is the density and \( K \) is the Gladstone–Dale constant. This equation holds quite well for gases. The constant \( K \) is a function of the particular gas and varies slightly with wave length. Index of refraction or refractive index \( n \) is defined as \( n = \frac{c_o}{c} \), where \( c_o \) is the speed of light in vacuum and \( c \) that in the medium.

\[
n = n(\rho)
\]

When encountering a flow field of varying density, light passing through one part of the flow field is retarded differently from that passing through another part.

![Diagram of light ray deflection](image)

**Fig.8.1 Effect of change of Refractive Index on a ray of light**

As shown in Figure 8.1, light ray is deflected from original direction and reaches \( Q^* \). \( Q \) and \( Q^* \) will coincide if at all planes normal to the incident ray \( n \) is constant. The optical path covered by the deflected ray is different from that of the undisturbed ray. It is possible to measure

(a) displacement \( QQ^* \)

(b) the angular deflection \( \Delta \theta \)

(c) the path difference between the two rays

The Table 8.2 sums up the three different methods for optical flow visualisation.
Table 8.2 Comparison of the three optical methods of flow visualisation

<table>
<thead>
<tr>
<th>Method</th>
<th>Quantity measured</th>
<th>Sensitive to the change of</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shadow</td>
<td>Displacement</td>
<td>$\frac{\partial^2 n}{\partial x^2}$</td>
</tr>
<tr>
<td>Schileren</td>
<td>Angular deflection</td>
<td>$\frac{\partial n}{\partial x}$</td>
</tr>
<tr>
<td>Interferometer</td>
<td>Phase change</td>
<td>n</td>
</tr>
</tbody>
</table>

8.3.2 Deflection of light ray in a medium of constant density gradient

Fig.8.2: Effect of a constant gradient of refractive index on a wave front
Let OZ represent the undisturbed path of a ray of light and let A and B represent points on an element of the wave front at O. Suppose that a disturbance is introduced into the light path with a constant gradient of refractive index in the direction normal to O. If \( n \) is the refractive index at O and \( n_A \) and \( n_B \) are the refractive indices at A and B respectively then

\[
\begin{align*}
  n_A &= n + \frac{\partial n}{\partial x} dx \\
  n_B &= n - \frac{\partial n}{\partial x} dx
\end{align*}
\]

and the corresponding optical velocities are related by the equations

\[
\begin{align*}
  v_A &= v \frac{n}{n + \frac{\partial n}{\partial x}} dx \\
  v_B &= v \frac{n}{n - \frac{\partial n}{\partial x}} dx
\end{align*}
\]

The ray will therefore be deflected through any angle \( \delta \theta \) and with a local radius of curvature \( R \) given by

\[
\frac{1}{R} = \frac{1}{n} \frac{\partial n}{\partial y}
\]

The total deflection \( \theta_x \) in a plane normal to OY is given by

\[
\theta_x = \int \frac{1}{n} \frac{\partial n}{\partial x} ds
\]

and in a plane normal to OX is given by

\[
\theta_y = \int \frac{1}{n} \frac{\partial n}{\partial y} ds
\]

For the purpose of calculating the density it is usually assumed that the deflection from the undisturbed path is infinitesimally small so that ds may be replaced by dz in equations above.
### 8.3.3 The schlieren method

The set up for schlieren method which is most commonly employed is shown in Figure 3.

**Fig.8.3 Schlieren set-up employing convex lenses**

If the source is of uniform intensity and the angle $\omega$ is sufficiently small, the image obtained at the screen will be of uniform brilliance. If now an opaque cut off (knife edge) is introduced in the plane K so that a fraction of the image of the source is obscured, the illumination at the screen will remain uniform but will be reduced. In the disturbed flow part of the beam of light is deflected and the corresponding part of the image of the source moves a distance $\Delta a$ relative to the cut off. This is illustrated in Figure 8.3.

This movement and the change of illumination are proportional to the angular deflection $\theta$, observations of the change of illumination will indicate the density gradient in the tunnel.
Part of the rays are cut off by the knife edge in b. In c, more rays reach the screen proportional to a+Δa.

**Fig.8.4 Deflection of the rays of light with respect to the knife edge**

Assuming θ to be small

Δa = f₂θ

The contrast is given by

\[ \frac{ΔI}{I} = \frac{Δa}{a} \]

where, ΔI is the change in illumination at the screen and I the original value.

Hence,

\[ \frac{ΔI}{I} = \frac{f₂θ}{a} = \frac{f₂}{a} \int \frac{1}{n} \partial n \partial x \, dz \]

If high sensitivity is required the quantity ‘a’ will be made as small as possible.

### 8.3.4 Colour schlieren

It is always good to visualize flow fields of graded expansion and compressive regions using the colour schlieren arrangement. The principle of operation of colour schlieren is simple and is briefly presented in this section.
According to Gladstone Dale equation

\[ n - 1 = K \rho \]

variation of \( K \) with \( \lambda \) is marginal

\[
\frac{dn}{n} = \frac{dK}{K} + \frac{d\rho}{\rho}
\]

For a compression \( \frac{d\rho}{\rho} \) is + ve.

Hence, \( \frac{dn}{n} \) should be + ve.

For implementing the colour schlieren, the white light is split in to its constituent colours by means of a dispersion prism. The colours in the VIBGYOR spectrum have varying values of refractive index. The value of refractive index is largest for violet and least for red.

Fig.8.5 The change in refractive index with colour

Visualisation of the graded density regions can be easily obtained if the green colour is selected as the background colour.
8.3.5 Shadowgraph method

The shadowgraph method requires simpler optical apparatus than either of the other two methods. It is admirably suited to the demonstration of compressibility phenomena (particularly to the visualisation of shock waves and wakes). It is least amenable to the numerical determination of the density in the field of flow.

In its simplest form the method consists of a light source on one side of the test section and a screen on the other.

As shown in Fig.8.5, if the refractive index gradient \( \frac{\partial n}{\partial x} \) is constant i.e. \( \frac{\partial^2 n}{\partial x^2} = 0 \) the deflected rays remain parallel as shown. If however \( \frac{\partial^2 n}{\partial x^2} \) is positive the rays are deflected and diverge as shown. If \( \frac{\partial^2 n}{\partial x^2} \) is negative deflected rays converge as shown in the Fig.8.6.

The convergence or divergence of the rays is very well understood if the bow shock in front of the blunt body in supersonic flow is observed in a shadowgraph. The shadowgraph image will have bright and dark bands as represented in Fig.8.7. In the case of the shock front, density gradients within the shock front are shown in Fig.8.8 which explains the dark and bright bands seen in the shadowgraph.
8.3.6 Interferometer method

Interference principle is illustrated in the Figure 8.9. As shown in the figure, two rays from a coherent beam reach P by two different paths. Consequently interference fringes are formed. Whether they reinforce or annul each other depends on their relative phases, which in turn depends on the lengths of their paths. If they pass through identical media the only path difference is due to the geometrical disposition.
If a different medium is kept in the path of the ray (2), the effective path of that ray is changed and with it the order of interference at P. If the index of refraction in test section is increased from $n_1$ to $n_2$ the light speed is decreased from $c_1$ to $c_2$. Additional time for traversing the test section of width $L$ is

$$\Delta t = \frac{L}{C_2} - \frac{L}{C_1} = \frac{L}{C_0} (n_2 - n_1)$$

$L \times n$ is defined as the optical path length where $L$ is the width of the test section. Therefore, change in optical path length

$$\Delta L = C_0 \Delta t = L (n_2 - n_1)$$

The number of interference fringes shifted

$$N = \frac{\Delta L}{\lambda} = \frac{L}{\lambda} (n_2 - n_1) = \frac{(\rho_2 - \rho_1)}{\lambda} KL$$

Sensitivity

$$\text{Sensitivity} = \frac{N}{\Delta \rho} = \frac{KL}{\lambda} = \frac{n-1L}{\rho \lambda}$$
The sensitivity of interferometer decreases with increase in density. If a medium of different refractive index is introduced into one of the two interfering light rays, a fringe shift occurs from which the refractive index of the disturbing medium relative to the surrounding medium may be reduced. Interferometers are often used in quantitative studies. The Mach-Zender interferometer is widely employed for aerodynamic studies.

### 8.3.7 Glow discharge visualization for low density flows

Optical methods need a minimum level of density. In low density atmosphere, radiative characteristics of gas are employed for visualisation. The electric discharge of gas at low pressures is accompanied by the emission of light.

The method involves the acceleration of the free electrons and ions in the control volume by the electric field. Their collisions with neutral molecules produce secondary ions and electrons. These primary and secondary electrons excite gas molecules which emit radiation on spontaneous transition into the ground state. The emission intensity is a function of gas density.
Exercise

Answer the following

1. What are the requirements of tracer particles used for flow visualization?

2. Why tracer methods cannot be used for visualization of compressible flows?

3. What is Gladstone-Dale equation? How does it explain the deflection of a light ray in a compressible medium?

4. Differentiate the three methods schlieren, shadowgraph and interferometry.

5. Draw a schematic of the schlieren system making use of concave mirrors.

6. Marking the components and the test section.

7. Why the lenses/mirrors used in schlieren system has large focal length?

8. Explain the principle of operation of colour schlieren.

9. Why the bow shock visualized through shadowgraph has bright and dark bands?

10. Explain the interferometric principle?

11. On what factors does the sensitivity of interferometer depend?

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