LAB 8 - Shadowgraph Visualisation Technique
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AE351
29th March 2022

- **OBJECTIVE:**

1. To study the shock structure on the solid body using ***schlieren visualisation*** technique.
2. To study the shock structure on the solid body using ***shadowgraph visualisation*** technique.

Part 1:
• Shock images will be shared on a wedge with zero pitch angle
• The wedge angle will be provided (θ)
• Measure the shock angle from the given images (β)
• ***Estimate flow Mach number (M) using M- θ− β relation***

Part 2:
• The wedge provided at a small pitch angle of δ at the same M
• The wedge angles and hence the shock angles are different for top and bottom surfaces.
• ***Measure the shock angles for the top and bottom surfaces and estimate δ***

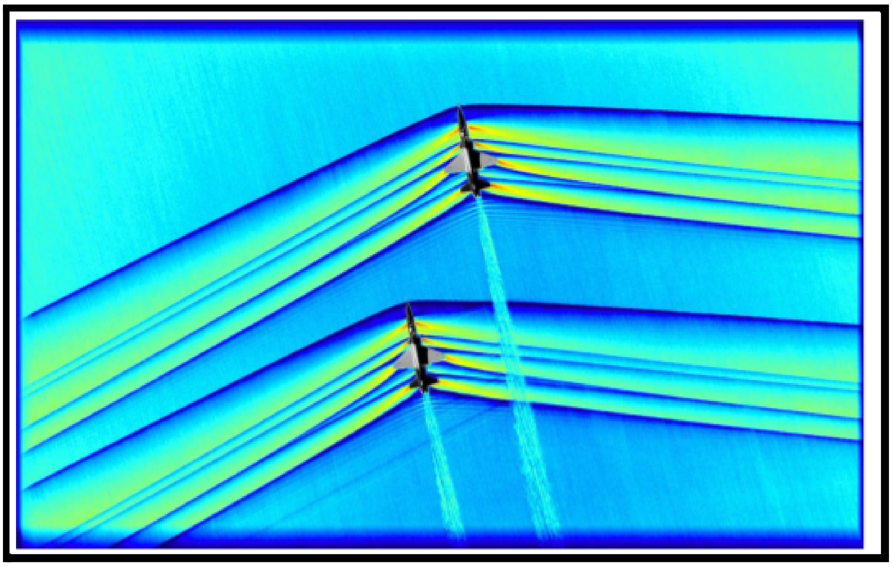
- **INTRODUCTION AND THEORY:**

- A ***shock wave*** is a type of propagating disturbance that moves faster than the local speed of sound in the medium. Like an ordinary wave, a shock wave carries energy and can propagate through a medium but is characterised by an abrupt, nearly discontinuous, change in pressure, temperature, and density of the medium .

- Capturing and detection of shock waves are extremely important as various performance parameters of an aerospace object are wildly affected by the presence of shocks.

Density gradient across the shock wave is visualised to capture or detect shock waves.

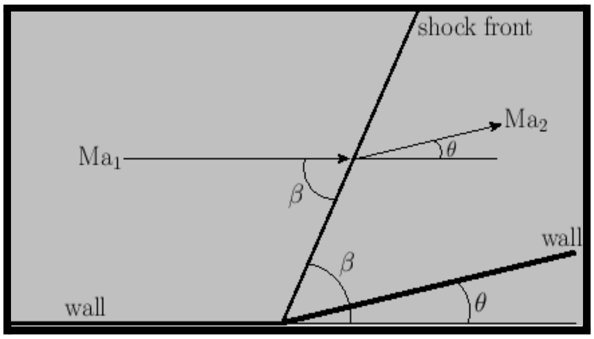
In ***schlieren visualisation -*** Illumination of the picture on the screen is proportional to the first derivative of the density $\frac{\partial \rho}{\partial x}$. [***schlieren visualisation is Clearer but images are inverted***]
In ***shadowgraph visualisation -*** Illumination of the picture on the screen is proportional to the second derivative of the density $\frac{\partial^2 \rho}{\partial x^2}$



FORMULAE:

1. $\theta - \beta - M\, relation$:

$$tan(\theta) = 2cot(\beta)[\frac{M^2 sin^2(\beta) - 1}{M^2(\gamma + cos(2\beta)) + 2}]$$



LIST OF SYMBOLS:

P_0 → Stagnation pressure
T_0 → Stagnation temperature
P_a → Ambient Pressure
NPR → Nozzle Pressure Ratio

A_x → Cross-sectional area at location x
A* → Cross-section area at throat
M → Mach number

P_{sc} → Settling chamber pressure
P_x → Pressure at location x
γ → Specific heat ratio of air

θ → Wedge Angle
β → Shock Angle

- **EQUIPMENT AND OPERATING CONDITIONS:**

The experimental setup includes:

1. **Supersonic wind tunnel :**

The schematic of the blowdown tunnel is shown in figure 1. In general ***Blowdown tunnels*** are used to test the models from high subsonic to supersonic flow conditions. The ***Laval nozzle*** is used to generate the desired Mach number in the test section.
The test section with size 225mm x 175mm is placed at the end of a de Laval nozzle. Basically, the Mach number in the test section is determined by pressure and temperature in the settling chamber and the area ratio between the test sections on the nozzle throat.
The test models are fixed in the test section by using a support. The air is pumped into a closed high pressure tank upstream of the settling chamber. At the same time, air is pumped out of a closed low pressure chamber downstream of the test section. As the flow expands in the nozzle, the pressure decreases and any moisture in the tunnel may condense and liquefy in the test section. To avoid condensation, air is brought into the tunnel through a dryer bed. A second throat is used downstream of the test section to shock down the supersonic flow to subsonic before entering the low pressure chamber or silencer

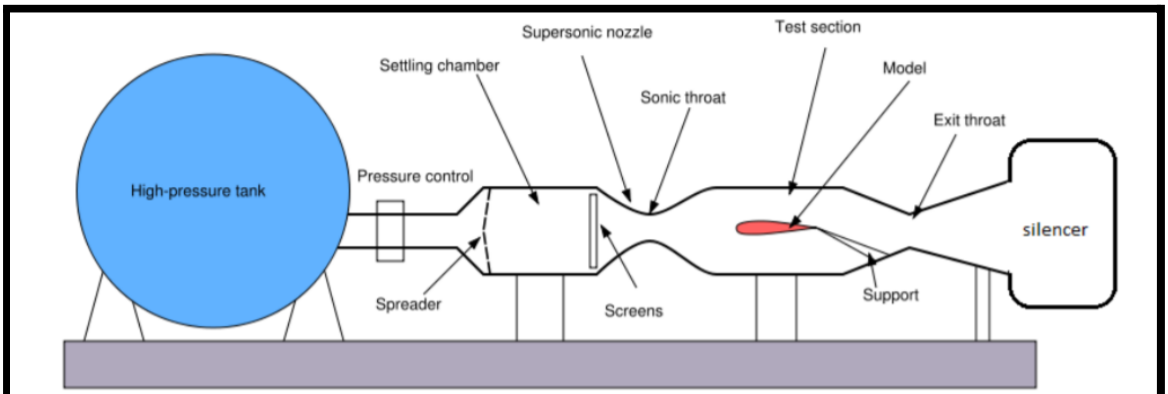


Figure1. Schematic representation of supersonic wind tunnel

2. **De-Laval Nozzle :**

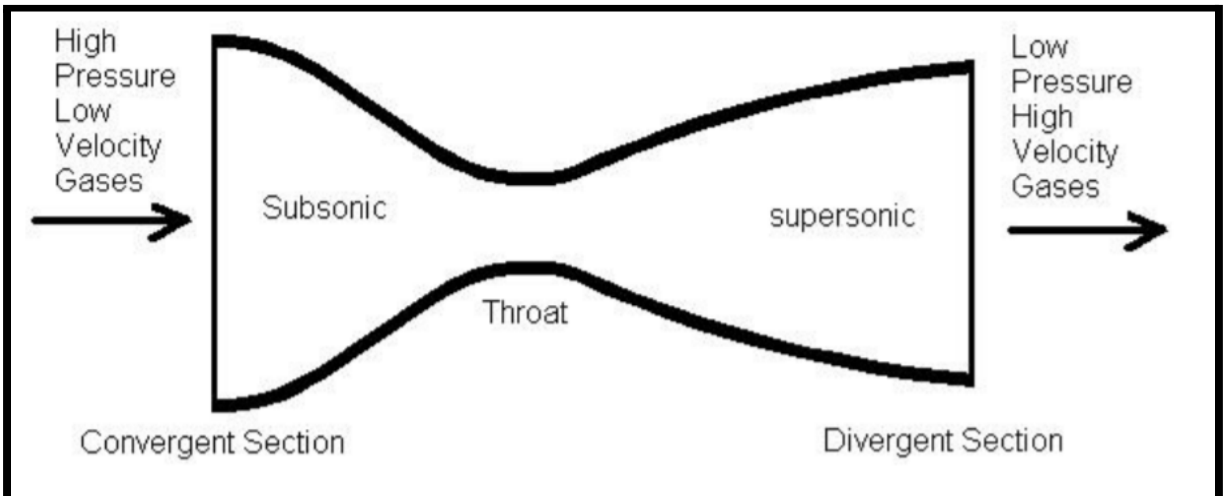


Figure 2. Schematic of de Laval Nozzle

3. **Light Source and Mirror :**

For schlieren visualisation -

a. A 5W Laser is used as a light source. In general a small intense halogen lamp is sufficient.
b. Two parabolic mirrors of 200 mm diameter and thickness of the mirror glass about 25 mm

For Shadowgraph visualisation -

a. A 5W Laser is used as a light source.
b. In general Helium spark arc light source and 150 mm diameter concave mirror is sufficient.

4. **Focusing Lens & Knife edge :** ***[Required for Schlieren visualisation only]***

This lens is positioned in the schlieren system in such a way that a flow field is focused on the screen. An ordinary double convex is used. Any straight, sharp edged opaque object mounted on an adjustable stand will be sufficient to serve as a knife edge.

5. **Electronic pressure scanners :**

The pitot pressure sensed by the probe was measured using a PSI model 9016, 16- channel pressure transducer. The model 9016 transducer is capable of measuring pressures up to 300 psi, which is approximately 20 atm. The accuracy of the transducer (after re zero calibration) is specified to be ± 0.15% full scale. Also, transducer offset errors were eliminated by performing a re-zero calibration prior to every run.

6. **Scanner support module :**

The application software developed using the LabVIEW links the host computer to the pressure scanner via TCP/IP communication. The application software performs all the required functions like initialise, reset, and re- zero calibration and read pressure

- **PROCEDURE:**

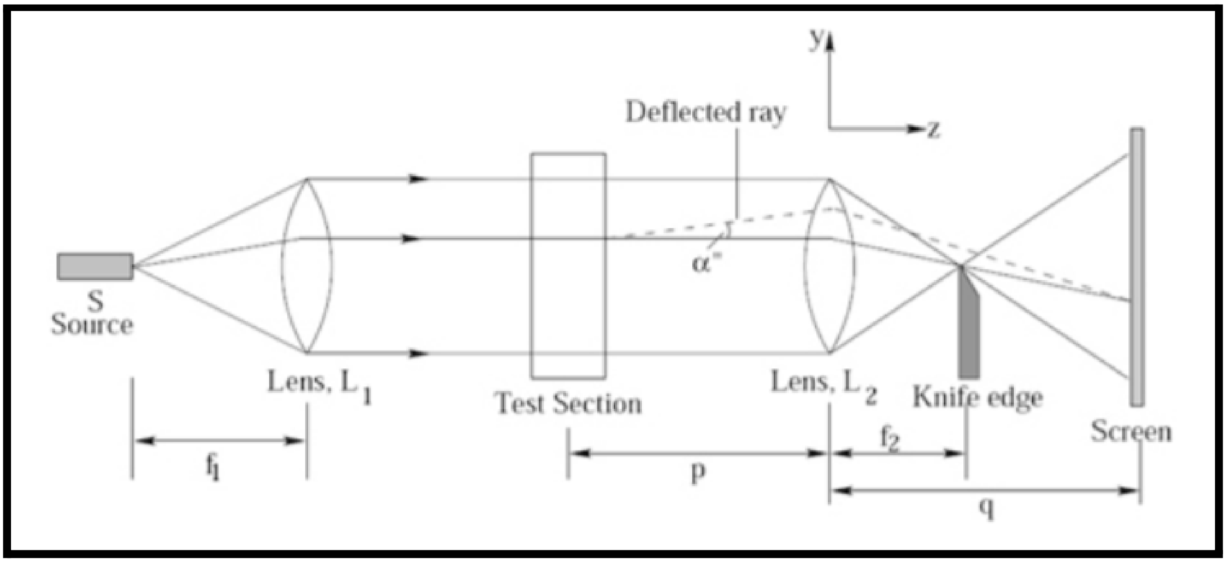
For schlieren visualisation :

1. Familiarise with the general layout and major components of the wind tunnel and the **Schlieren** and **shadowgraph** system.

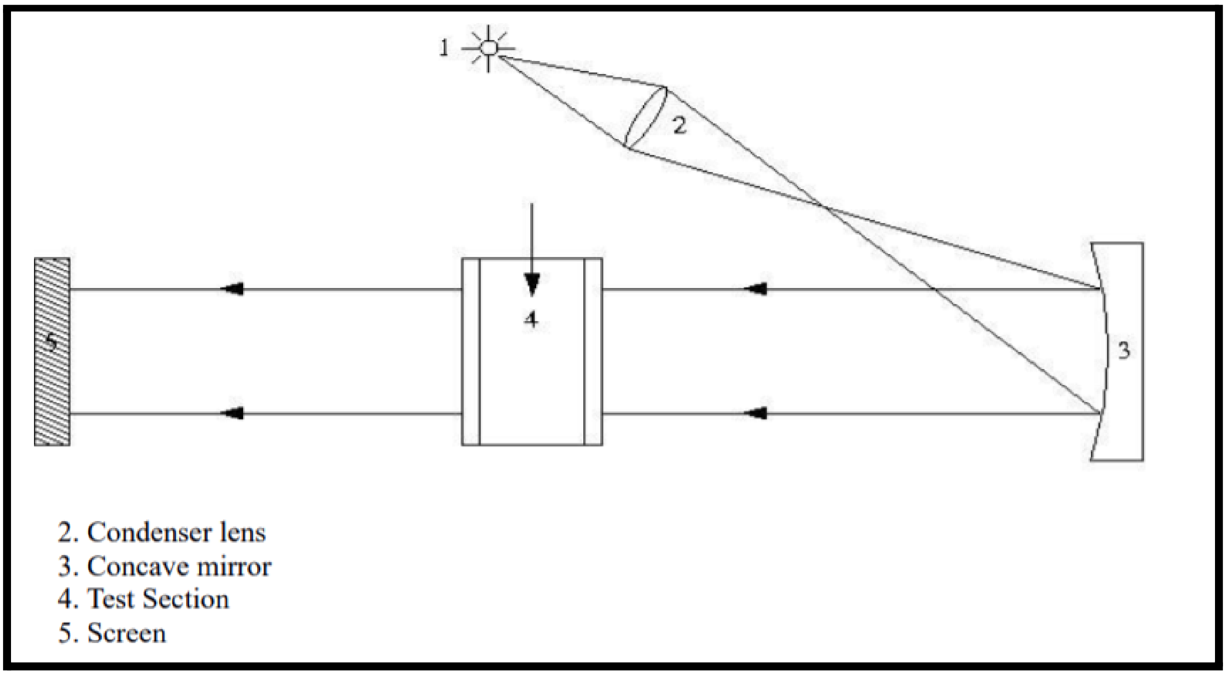
2. The stagnation pressure (Po), temperature (T0) and nozzle area ratio (A/A*) will determine the Mach number (from isentropic relations) in the test section of the wind tunnel. The settling chamber total pressure (Po), maintained constant during a run by controlling the pressure regulating valve.

3. The light source was collimated by the condenser lens and then brought to the concave mirror. The parallel beam from the mirror was made to pass through the jet flow field and projected on the screen. The photographs of shadowgraph images of shock-train on the screen were taken directly by using a camera. The arrangement of mirror and light source are shown in Figures below.

4. the visualised images on the screen for a given Mach number using a camera.



Schematic Representation of the Schlieren System



Schematic Representation of the Shadowgraph System

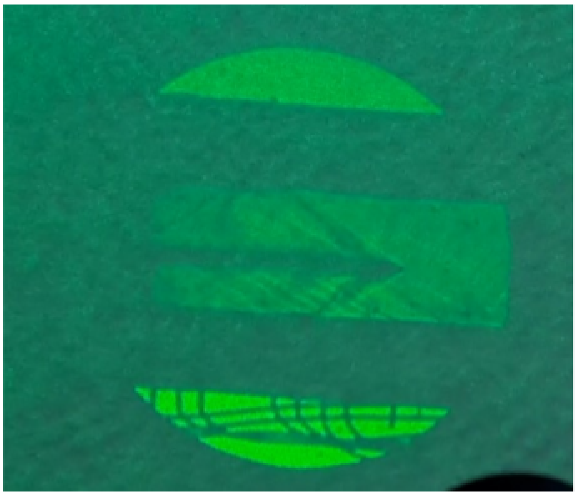
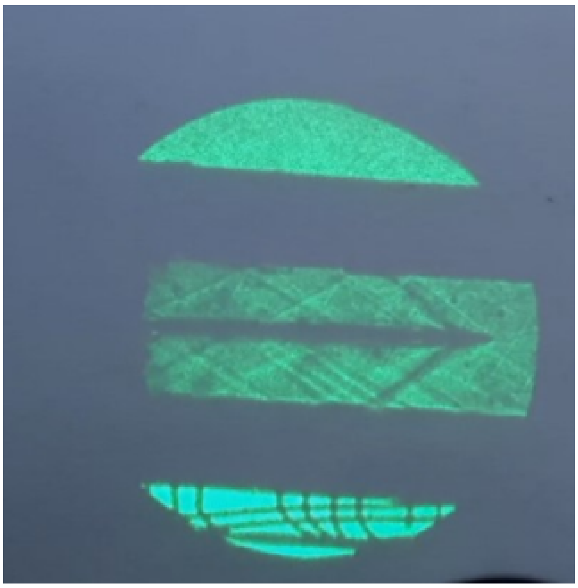
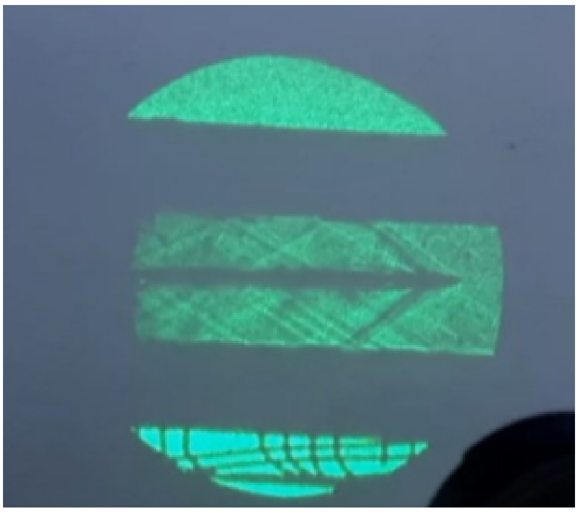
Some important Dimensions:

Wedge Angle	**15°**
γ_{air}	**1.4**

Measured Data:

- **RESULTS AND DISCUSSION :**

  (a) Calculations and Plots

<table>
<tr><td colspan="2">0 Deflection [cylindrical body is at 0° wrt horizontal]</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Schlieren</td><td>Shadowgraph</td></tr>
<tr><td colspan="2">With Deflection</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Schlieren</td><td>Shadowgraph</td></tr>
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Wedge Angle θ = 15°

- $\theta - \beta - M\, relation:$

$$tan(\theta) = 2cot(\beta)[\frac{M^2 sin^2(\beta)-1}{M^2(\gamma+cos(2\beta))+2}]$$

<u>Case 1: No deflection</u>

β will be same both above and below the wedge as flow is symmetric.

From Schlieren β = 34.16°	**M1 = 2.76625**
From Shadowgraph β = 36.41°	**M2 = 2.54344**

We the mach number of the flow , M = (M1 + M2)/2 = 2.65

<u>Case 2: With Deflection</u>

β will Not be same for both above and below the wedge as flow is Not symmetric wrt to the wedge .

For M = 2.65

From Schlieren	$\beta_{\text{shock above the wedge}}$ = 36.654°	$\theta_{\text{shock above the wedge}}$ = 16.259°
From Shadowgraph	$\beta_{\text{shock above the wedge}}$ = 38.022°	$\theta_{\text{shock above the wedge}}$ = 17.473°
$\theta_{\text{shock above the wedge}}$ = (16.259° + 17.473°) / 2 = 16.866° $\beta_{\text{shock above the wedge}}$ = (36.654° + 38.022°) / 2 = 37.338°		

From Schlieren	$\beta_{\text{shock below the wedge}}$ = 37.5°	$\theta_{\text{shock below the wedge}}$ = 17.015°
From Shadowgraph	$\beta_{\text{shock below the wedge}}$ = 40.78°	$\theta_{\text{shock below the wedge}}$ = 19.789°
$\theta_{\text{shock below the wedge}}$ = (17.015° + 19.789°) / 2 = 18.402° $\beta_{\text{shock below the wedge}}$ = (37.500° + 40.780°) / 2 = 39.140°		

Let Pitch angle be **δ** .

$\theta_{\text{shock above the wedge}} = \theta - \delta$
$\theta_{\text{shock below the wedge}} = \theta + \delta$

So $\delta = (\theta_{\text{shock below the wedge}} - \theta_{\text{shock above the wedge}}) / 2 = 0.768°$

1. Explain the shock structure on the solid body.
2. Comment on the nature of the shocks and explain inconsistencies, if any

Initially As the flow develops a strong shockwave is formed just ahead of the cylindrical body. The shockwave is oscillating because of the fluctuations and the instabilities in the flow field. Also there are droplets which are formed because of the condensation. A strong bow shock is formed that is standing just ahead of the cylindrical body. The shockwave is almost parabolic in shape

Oblique shocks are formed over the conical surface with parameters as mentioned above .

Sources of Error:

1. Do not exceed the pressure limits of the settling chamber.
2. Make sure that there are no loose parts and there are no objects placed inside the duct.
3. Make sure that the pressure ports are not blocked by dust or any other materials.

4. In the test section constant conditions need to be provided by controlling a pressure regulator valve.
5. Knife-edge needs to be aligned properly to obtain sharp images of the flow field.
6. Do not block the laser while it is on.
7. Screen needs to be placed close to the test section to have proper visibility of the image.

Conclusion :

1. *Mach number of the Flow ,* ***Ma = 2.65***

2. *Pitch angle* **δ = *0.768°***
    - $\beta_{\text{shock above the wedge}}$ **= 37.338°**
    - $\beta_{\text{shock below the wedge}}$ **= 39.140°**

- **Reference :**

- Pictures from Google, Lectures and Lecture Notes of AE351 (Lab8)
- http://www.dept.aoe.vt.edu/~devenpor/aoe3114/calc.html
- http://www.dept.aoe.vt.edu/~devenpor/aoe3114/CD%20Nozzle%20Sim/index.html

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