FLOW VISUALIZATION
FOR SUPERSONIC FLOW PAST A WEDGE

The Mach 4.0 nozzle will be used in the supersonic wind tunnel. This permits the use of the top mounted sting to support models (wedge, cone, blunt body). The wedge used is approximately 29 degrees total angle and can be mounted at various angles to the flow. Each surface of the wedge has a static pressure tap (or several connected taps).

1. Instrumentation
(a) PSI pressure measurement system and computer
(b) Optics for schlieren and/or shadowgraph
(c) Nikon Digital camera

2. Measurements
(a) Static wall pressures on the wedge surfaces at three model angle settings (0, 5, 10 degrees).
(b) Settling chamber stagnation pressure
(c) Schlieren and shadowgraph photos of the wedge mounted in the test section. A test model (wedge) will be installed in the test section in the optical path to produce an oblique shock. "Mach lines" from the top and bottom tunnel walls will also be present. The schlieren and/or shadowgraph mirrors, light source and slit should already be aligned. If necessary, adjust the schlieren knife edge and camera. Obtain schlieren and/or shadowgraph pictures during supersonic operation. Each student will receive digital photos for each angle of attack.

Schlieren and Shadowgraph Methods

General Description

Optical methods are very powerful and relatively simple ways of studying supersonic flows. Such flows involve large density changes which lead to large changes in the index of refraction. Uniform light beams will be distorted by the index of refraction changes, providing visualization of the flow features. Read one or more of the listed references that are ON RESERVE IN THE LIBRARY.

A double-mirror schlieren and/or shadowgraph system, like the one shown in figure 1 is set up in the supersonic lab. The mirrors are spherical, axial mirrors, 11.75 inches in diameter with a focal length of approximately 82.4 inches. An additional plane mirror "folds" the optical path located on the camera side. The light source and knife-edge should be located on the opposite sides of the collimated optical path and as near as possible to it to minimize the off-axis aberrations (coma and astigmatism). The light source is a 1-2 microsecond General Radio Strobatac which can be remotely triggered with a cable switch (button).

The schlieren is sensitive to the spatial derivative of density (and thus index of refraction) in the flow field. A shadowgraph is sensitive to the second derivative of the density, so it displays sharp variations, as across a shock, more clearly. All originating pencils of light pass through the test section and are focused at the same plane. Without an obstruction such as the knife edge the recording screen would be uniformly illuminated. The presence of a knife edge in a schlieren system decreases the illumination at the recording plane. The knife edge intercepts more light from some points in the test section plane than from others, resulting in light and dark regions, or “schlieren” on the recording plane. “Schlieren” is the German word for “streaks”. The distance from the phase object (schlieren field) to the second mirror, O D, is greater than the focal length of the mirror, f, and a real image is formed at a distance

$$l = \frac{OD\,f}{OD - f} \qquad (1)$$

measured from the mirror. Therefore, the system can be operated without a camera lens by placing the film in the plane of the primary image. This has been done in the past using a Polaroid camera which provides a large image capturing plane. However, this lab will use a Nikon digital camera with a lens. The image is, therefore, focused on the camera lens rather than directly onto the small recording plane inside the digital camera. The magnification between the object and its image is

$$m = \frac{f}{OD - f} \qquad (2)$$

and varies from 0.7 to 0.94 for OD varying from 200” to 170”, respectively. A copy of a schlieren photograph is in figure 2.

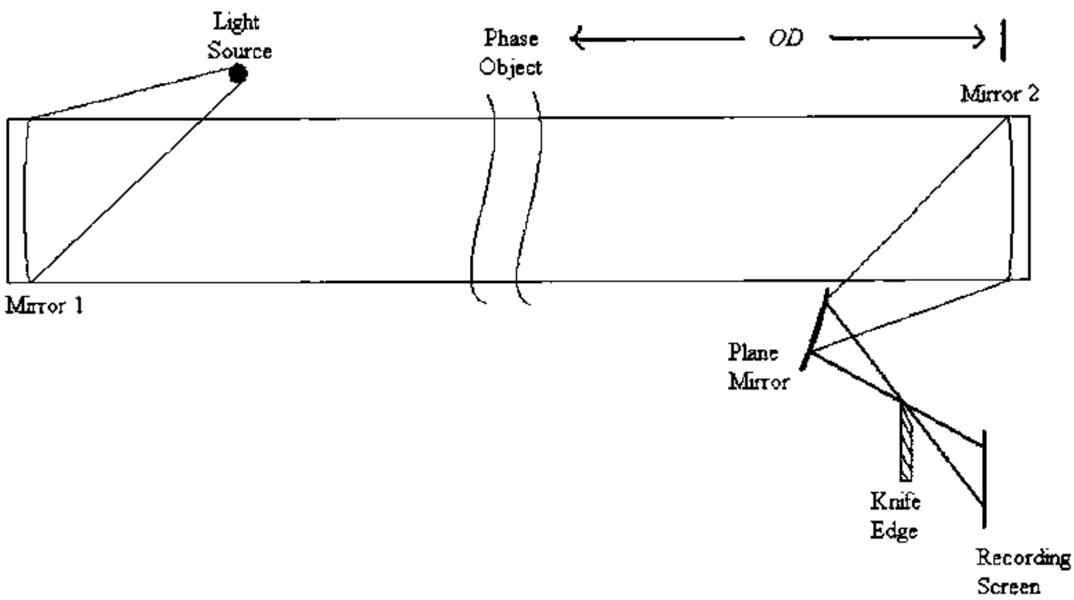

Figure 1- Two Mirror Schlieren System

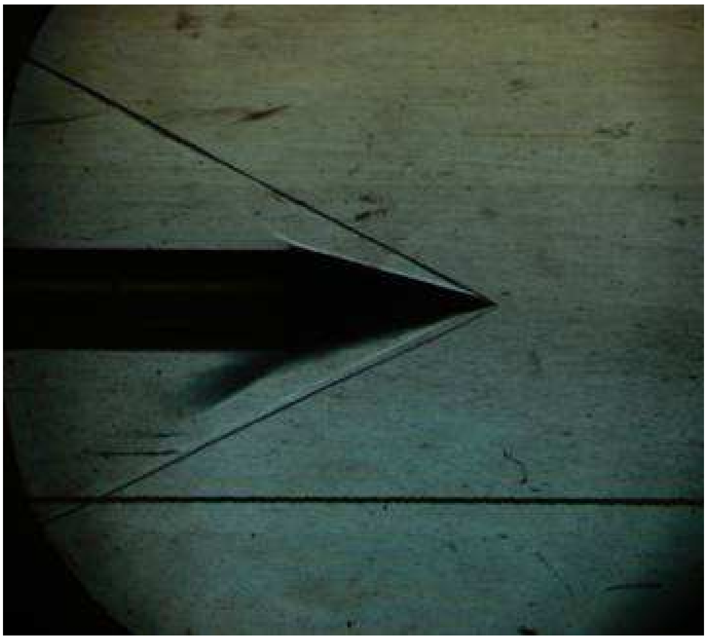
Figure 2 – Typical schlieren photo

Apparatus for Shadowgraph

The setup of a typical Shadowgraph system is shown in Figure 3. Illumination is provided by a 500mW Helium Neon laser firing though a microscope objective. The light is first reflected off a 12" parabolic mirror with a focal length of 80 inches. This produces a beam of collimated light which passes through the test section and illuminates the wedge.

The image is then reflected from a 14" flat mirror to a 6" parabolic mirror with a focal length of 24 inches. The image is thereby focused onto the Imacon 468 digital camera. The camera contains 4 CCD arrays which allow high-speed scanning of the arrays. This setup will not be used for this experiment and shadowgraph photos will be obtained in a similar manner as the schlieren photos, but with the absence of the knife edge.

Note that the alignment of the digital camera and the parabolic mirror may produce a slightly distorted image. The vertical scale factor is not necessarily equal to the horizontal scale factor. To correct for this effect a US nickel is taped to the window. The image of the nickel should be a circle, but might appear initially as an ellipse. By comparing the major and minor axes of the ellipse the difference in horizontal and vertical scaling may be determined.

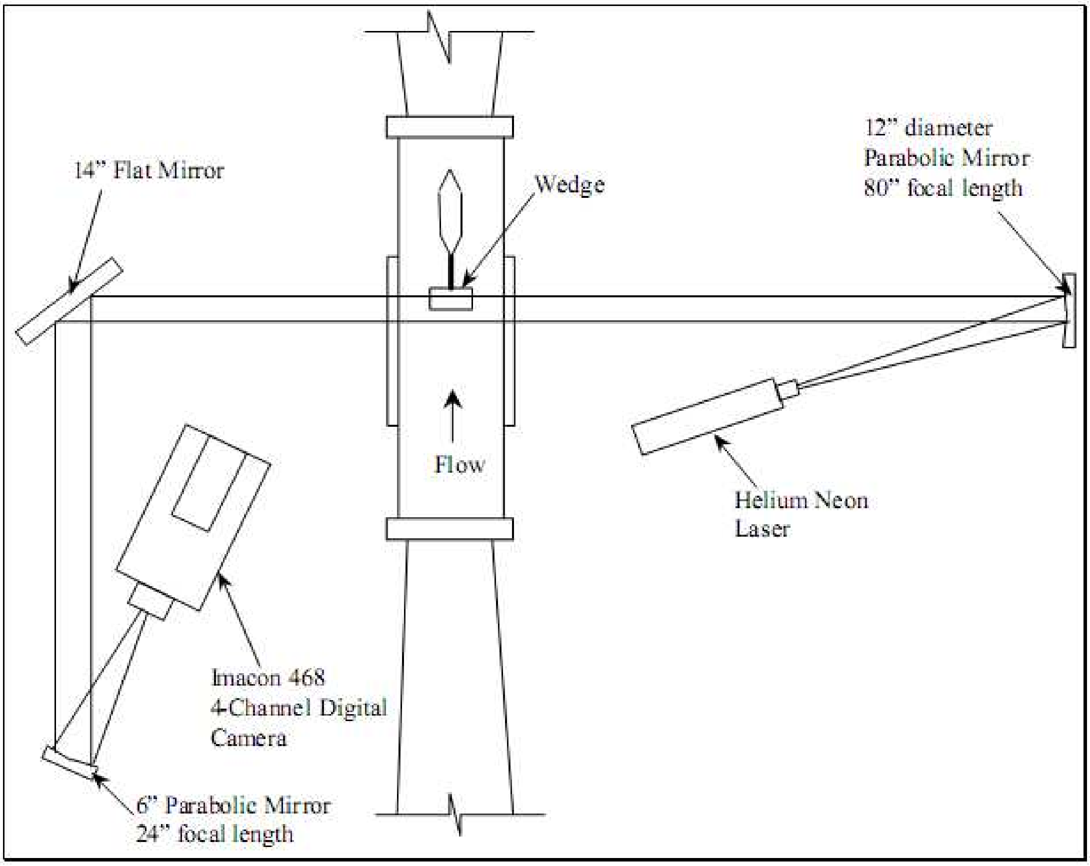

Figure 3: Shadowgraph setup

Apparatus for Schlieren

(1) Light Source System. Consists of a General Radio Model 1538-A Strobatac, convex lens (f ~ 7 inches), and adjustably-mounted light slit. Convex lens has one degree of freedom (longitudinal). Slit has three degrees of freedom: longitudinal, rotational, and aspect ratio(i.e. slit width).

- **Slit should be normal to the flow density gradients of interest**.
- Slit must be exactly at the focal point of the convex lens.
- Slit opening should be about one millimeter wide.
- Position of light bulb may need adjustment to focus light exactly on slit opening.
- Bulb housing can be rotated by 90 degrees if necessary to align filament with slit.
- For best quality schlieren photos, bulb housing, lens, and slit-mount should be covered on three sides to prevent stray light from contaminating photos. A bent piece of card board is sufficient.

Strobotac settings: time-averaged schlieren: Set Strobotac to 40000 rpm continuous and use a shutter to control film exposure.

(2) 11.75” concave mirror, focal length f = 82.5 inches
(3) Location of flow feature interest (the wedge).

(4) 11.75” concave mirror, f = 82.4 inches. Object distant (= OD = distance from (3) to (4)) should be greater than *f* and should satisfy equation (1)
(5) Flat mirror and knife edge system. Mirror is approximately ten inches in diameter. It can be angled by adjusting the thumb-screws located on the back of the mirror. Knife edge can be moved along the bench by loosening the bottom screws, and can be more precisely positioned via a track-mount, which is controlled by a large knob near the bottom of the apparatus, and larger adjustments can be made by using an Allen-wrench to loosen the back plate (which holds the actual knife edge) for rotation.

Procedure

1) Examine the Shadowgraph and/or Schlieren system and be sure you understand how it works (BE CAREFUL not to bump any of the equipment out of alignment).
2) The digital camera will be set up by a graduate lab assistant.
3) The wedge is currently mounted at either 0, 5, or 10deg angle of attack.
4) A horizontal reference string and US nickel should be attached to the camera side window to allow scaling and ease of angle measurment
5) Turn on the Strobotac light source
6) A graduate assistant will begin the tunnel run sequence (Make sure everyone is on the outside of the safety wall)
7) After the tunnel engages, wait approximately four seconds and fire the digital camera to acquire an image.
8) Turn off the light source.
9) Mount the wedge model at the next desired angle of attack.
10) Repeat steps 4-8 until images are acquired at 0, 5, and 10 degrees angle of attack.

Report

1) Calculations
  a) From the flow turning angle, δ, and the shock angle, θ, calculate the upstream Mach number, M1. Also calculate the shock angle based on δ and M1=4.0 for each angle of attack.
  b) Compute the pressure, P2, behind the oblique shock using the measured values of the shock angle, θ, Mach number, and stagnation pressure, Pt1. Compare the result with the measured values for each AoA.
  c) For a non-zero turning angle, pick an image where the boundary layer is clearly visible on one surface (the bright region). Estimate the boundary layer thickness at a few points by scaling it off the image. You may determine the measurement scale factors from the image of the nickel. The diameter of a nickel is 0.835”. The BL may be difficult to measure, because it is very thin at M1= 4.0
  d) Assuming a flat plate flow, calculate the boundary layer thickness over the chosen surface. You may use the numerical methods from your boundary layer class or analytical solutions. Remember to calculate the flow to transition before using turbulent solutions.

2) Discussion

a) Compare the upstream Mach number and shock angle calculations for the different angles of attack.

b) How do the pressure ratios compare for each angle of attack and does this make sense?

c) Discuss the approximate locations of the measured boundary layer thickness and how you measured them. Do they make sense?

d) How does the presence of the boundary layer affect the position of the shock wave?

e) Describe differences between theoretical and measured values and possible explanations. What are the sources of errors? Which methods are the most accurate?

f) Describe how the set-up should be changed to observe a normal shock

3) Plots

a) Measured and calculated values of θ versus the turn angle.

b) Pressure ratios over the top and bottom surfaces versus turn angle.

c) Plot the calculated boundary layer thickness development and the measured points versus distance along the surface of the wedge (from the nose).