MAE 352 - Experimental Aerodynamics II
Lab 2 – Shock Wave Analysis
Final report due date: 02/18/2018

Objective: Understand and implement Schlieren imaging technique for flow visualization and:

- Determine the shock characteristics of a 2-D wedge in supersonic flow.
- Plot the Θ-β-M curves for the wedge at different Mach numbers and compare it with theoretical data.
- Compare the Mach numbers obtained from the Θ-β-M relation and the isentropic relation.

Theory: Due to the large fluctuations in properties, specifically density, across a shock wave, it is possible to observe a shock wave using Schlieren photography. A Schlieren system consists of a strong, coherent light source, a slit, a set of mirrors, and a recording device. The light passes from the source through the slit to a mirror, in order to create a single large beam of light, which then passes through the test section, which is then reflected on a second mirror past a focal point (at the knife edge) to a recording, as shown in Fig. 1.

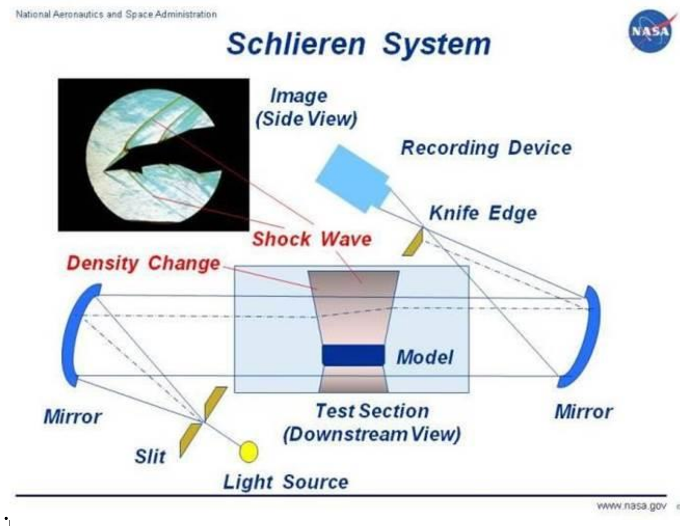

Figure 1: Schlieren system (Source: www.nasa.gov).

The following components make up the Schlieren system:

1. Light source and slit: The light source used is specifically designed to produce strong low diffusion rays which allow the visualization of density changes through the test section. The light source used at NCSU incorporates the slit into one unit. The slit refracts the light as it approaches the first mirror.
2. Mirror: The first mirror is concave and reflects the light in laminar beams through the test section. This process increases the clarity of the final image by reducing contamination brought on by diffusion of photons.
3. Test section: The test section houses the model. As shock waves are formed, the light passes through the test section at different speeds. The more dense the medium, the slower light travels through it. This is the fundamental theory behind Schlieren imaging.
4. Knife edge: At the focal point produced by the second mirror, a knife edge is placed to remove additional light diffused on its path. After the light passes the knife edge, the image increases in size proportionally to the distance past the knife edge.
5. Recording device: The image is then reflected off of a flat mirror and can be presented on the wall inside the room or be photographed for post experiment data processing. In our current setup, the light is projected directly on to the recording device.

The resulting image obtained using the Schlieren system (Fig. 2) can be used to predict the Mach number of the flow, using the angle of the formed shock, β. The angle of the formed oblique shock is a function of the Mach number, M_1, prior to the shock and the angle of the shape that forms the shock, Θ.

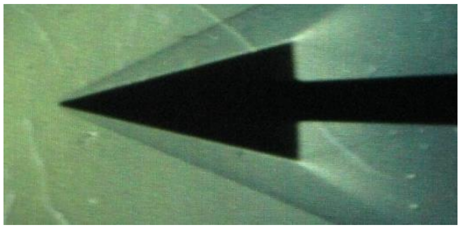

Figure 2: Image of an oblique shock in the NCSU Supersonic Wind Tunnel.

Observing the change in direction of the streamlines (over the shock) in Fig. 3, it is possible to create a relationship between the angle of the shockwave, the angle of the wedge, and the Mach number. If we separate the velocity components of the stream lines into a component parallel to the shock, *w*, and a component normal to the shock, *u*, making the relation,

$$\tan\beta = \frac{u_1}{w_1}$$

Observations from Fig. 3 shows that only the *u* component changes over the shockwave, with the *w* component remaining constant ($w_1 = w_2$). Therefore,

$$\tan(\beta - \Theta) = \frac{u_2}{w_2}$$

Applying standard isentropic relations, we obtain,

$$\frac{\tan(\beta - \Theta)}{\tan\beta} = \frac{u_2}{u_1} = \frac{2 + (\gamma - 1)M_1^2 \sin^2\beta}{(\gamma + 1)M_1^2 \sin^2\beta}$$

Simplifying the above equation, we obtain the Θ-β-M relation relating the wedge angle, Θ, shock angle, β, and freestream Mach number, M_1:

$$\cot\Theta = \tan\beta\left[\frac{(\gamma + 1)M_1^2}{2(M_1^2\sin^2\beta - 1)} - 1\right]$$

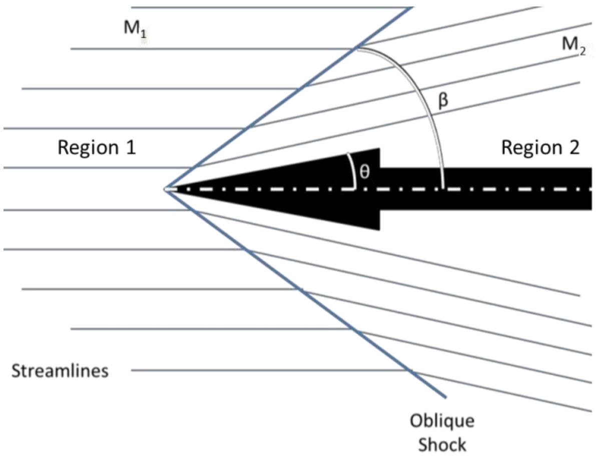

Figure 3: Schematic of an oblique shock.

Figure 4 shows the oblique shock angle, β, as a function of the wedge angle, Θ, for a few constant M_1 lines. The Θ-β-M relationship will produce two β angles for a given Θ and M_1, with the larger angle called a strong shock and the smaller called a weak shock. The chart assumes $\gamma = 1.4$, which is valid for an ideal diatomic gas. For a given Mach number, M_1, and wedge angle, Θ, and the oblique shock angle, β, the downstream Mach number, M_2, can be calculated. M_2 is always less than M_1. Unlike after a normal shock, M_2 can still be supersonic (weak shock wave) or subsonic (strong shock wave). The blue line separates the strong and weak solutions. Nature tends to focus on weak solution. Discontinuous changes also occur in the pressure, density and temperature, which all rise downstream of the oblique shock wave. Within the Θ-β-M equation, a maximum corner angle, Θ_{MAX}, exists for any upstream Mach number. When $\Theta > \Theta_{MAX}$, the oblique shock wave is no longer attached to the corner and is replaced by a detached bow shock. The weak shock is almost always seen experimentally [1].

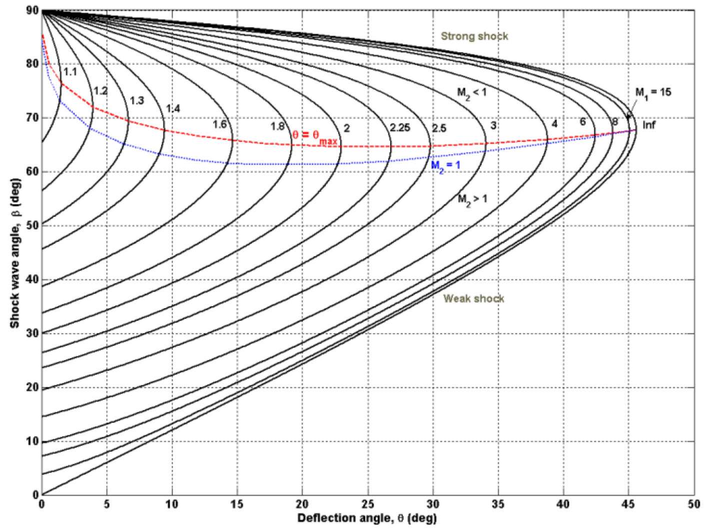

Figure 4: Oblique shock angle relation [1].

Experiment: Using the Schlieren system and pressure transducers, record the following data for varying wedge angle (Θ) and Mach numbers and capture the Schlieren images for the same conditions:

Table 1: Data collected for the shock wave analysis experiment.

time (s)	P_{01} (psi)	P_1 (psi)	P_{atm} (psi)	T_{01} (°F)
system clock	from WT transducer	from pressure transducer	from barometer	from WT transducer

Using the Schlieren images and the data from the pressure transducers, calculate the freestream Mach number and re-create Fig. 4. Note that all pressures obtained using the transducers are gauge pressures. Also, average out all the data collected after 2.5 seconds of tunnel run time.

The following constants can be used to help with your analysis:

1. Specific heat of dry air, γ: 1.4

In the final report,

- Plot the shock wave angle versus wedge angle for different freestream Mach number settings. Write an image processing code to extract the β values from the Schlieren images.
- Co-plot and compare your results with theoretical analysis (Fig. 4).
- Calculate and plot the Mach number vs. block number from the freestream static and stagnation pressure data using the isentropic relation and compare it to the Mach number obtained from the Θ-β-M relation. Additionally, compare this data with similar results from Lab-1.
- All results must be presented in SI units.
- Present your code in the Appendix.

References: [1] Academic Dictionaries and Encyclopedias (http://enacademic.com/dic.nsf/enwiki/1310426).