Assignment #9 : Nozzles and Shock Waves — ME 412

due 11/9/2016 before midnight via Learning Suite — 50 possible points

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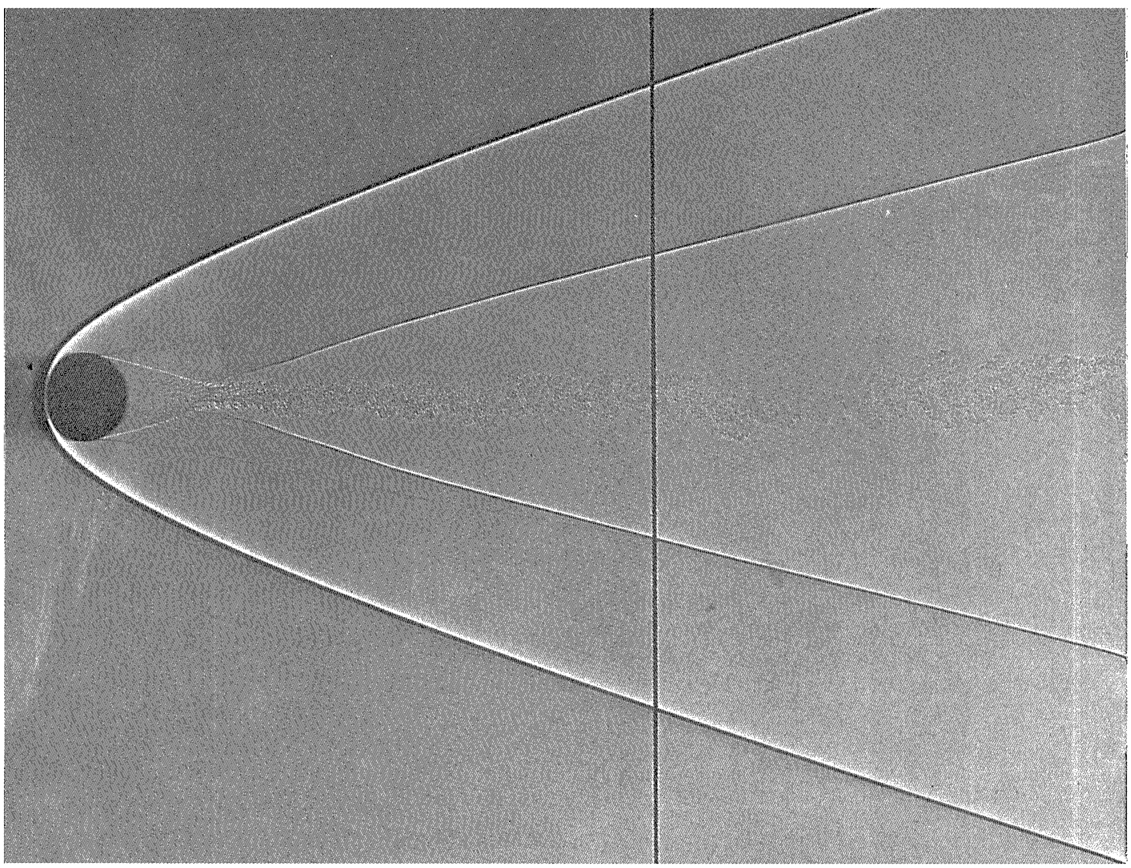
Project: Be sure you are continuing to make some progress on your projects.

9.1 Below is a shadowgraph of a sphere flying supersonically through air (from Van Dyke). Notice the coalescence of an N-wave that creates a double boom. The vertical line in the figure is just a reference cord.

(a) Far downstream, a bow shock weakens and becomes a Mach wave. Using that information, and the figure below, estimate the Mach number of the sphere.

(b) The freestream pressure and temperature are 1 atm and 350 K respectively. Compute the temperature, density, pressure, and Mach number of the air on the centerline, just downstream of the shock.

(c) Estimate the temperature and pressure at the stagnation point on the front of the sphere.



9.2 In this problem you will analyze the pressure distribution in a nozzle for three different scenarios (fully subsonic, shock wave, isentropic supersonic), and you will use three different analysis techniques: theoretical, experimental, and CFD.

The end goal is to produce plots of P/P_T as a function of station number (there are 7 stations) in the nozzle, where P_T is the total atmospheric pressure (upstream of the nozzle). Plot your results from each scenario on a different plot, but for each scenario put all three analysis techniques on the same plot. Make sure the plots are clearly labeled. In addition, the CFD case asks for a Mach number contour plot.

The nozzle has seven pressure ports. The diameters of the nozzle at the seven measurements locations from front to back are 10.43 mm, 10.59 mm, 10.87 mm, 11.18 mm, 11.38 mm, 12.0 mm, and 12.37 mm. The throat is located between the first and second measurement location and has a diameter of 10.34 mm. The exit diameter is 12.51 mm.

(a) **Experimental:** Perform this lab in a small group, but perform the calculations and write up individually. Instructions for running the lab are provided at the end of this document.

Take three datasets: one fully subsonic, one choked with a standing shock wave, and one choked with no shock in the nozzle (isentropic supersonic flow). You should be able to both see and hear the transition to choked flow.

Unfortunately, with the tear down of B38, we won't have a vacuum pump to power our nozzle until the annex is ready next year. I've posted the experimental data I recorded last year for you to use. You'll still need to read the lab instructions to understand the provided data.

(b) **Analytic:** Using the theoretical methods discussed in class, predict P/P_T at the same nozzle areas as in the lab for all three cases (subsonic, shock wave, supersonic isentropic). You must show all your work. If you use a programming language to help you, you must still write out the relevant equations/methods. Predicting the location of the shock is a bit more involved so you can just directly use the location you found in the lab. Use the information on shock location to then predict Mach number and pressure elsewhere.

Extra credit: predict the shock location theoretically and compare the result.

(c) **CFD:** Using Star-CCM+, simulate the three scenarios. This video tutorial on converging diverging nozzles may be helpful to refer to (we won't have a fuselage). Perform a compressible, **inviscid** simulation.

A geometry file is provided on our website. The geometry is a 2D slice of the nozzle. You will be solving this as an axisymmetric model. When selecting physics models, be sure to select Axisymmetric, not 2D (which means you must deselect "auto-select recommended models").

Also provided is a macro that might be helpful to export all reports to a file so you can plot the data elsewhere. The geometry file already has probes defined corresponding to the pressure tab locations. The macro will write out all the values at those locations if you make reports from the derived parts.

In additional to extracting pressures, **turn in a Mach number contour plot generated in Star-CCM+ for the shock wave case.**

(d) Discuss your results, sources of error, lessons learned, etc. This should be a thoughtful reflection (e.g., more than a sentence or two).

Lab Instructions

The nozzle in B38 is exposed to the atmosphere upstream, and is connected to a vacuum pump downstream. You will be able to regulate the back pressure by adjusting the valve. A pressure differential at each station is measured with a mercury manometer.

Start the vacuum pump:

- Double check that all valves are closed.
- Prime the pump. You should turn the crank until you see a drop fall from all three openings.
- Open the water valve.
- Turn on the power.
- Open the valve behind the machine.
- **Slowly** adjust the valve above the nozzle to reduce the back pressure.

WARNING: Adjust the valves slowly! If you adjust too quickly you could cause the mercury to fly out or other bad stuff. Also, do not put anything in the nozzles.

Collect data:

- Measure ambient pressure (valve fully closed). The large circular dial will give you the pressure reading. The outer set of numbers is the pressure in psf.
- Open the valve to a desired setting. Recall that you need to do one case fully subsonic, one case choked with a standing shock wave, and one case fully supersonic.
- Wait until the manometer levels settle and record the pressure at each station. The pressure measurement is given in inHg. Record also the pressure of the last manometer that is open to the atmosphere—that is your zero gauge point. In other words if you measure 7 in one station and 1 in the open tube, you should correct the gauge pressure at your station to 6 inHg (7-1). Remember, that a manometer provides gauge pressure, so you will need to use the measured atmospheric pressure to find the absolute pressure at each station. Be careful with units!
- Measure the back pressure. Again, use the outside set of numbers which is in psf. Note that the scale wraps around and for the last case (lower pressure) you will likely need to use the wrapped around (smaller) set of numbers.

Turn off the vacuum pump:

- Close the valve above the nozzle.
- Close the valve behind the machine.
- Turn off the power.
- Close the water valve.