GALCIT 6-Inch Shock Tube

Ae 104b

TA: Bryan Schmidt
Lab: Ludwieg Tube
Phone: 419.681.6128
bsschmid@caltech.edu

Winter 2013

1 Principle of a shock tube

All shock tubes consist of at least two sections: one called the driver section and the other called the driven section. We will cover the basics of two-section shock tube operation below. The GALCIT 6-Inch shock tube also has a third section–the test section–which allows careful control over the test conditions. How this affects basic shock tube performance will be discussed below.

In two-section shock tube operation, the driver and driven sections are filled with gases at different pressures and are initially separated by a thin diaphragm. The pressure in the driver section is greater than in the driven section and is slowly increased until the diaphragm ruptures. The rupture of the diaphragm creates a shock wave propagating in the driven section and an expansion wave propagating in the driver section, as shown on Figure 4. The moving boundary between the shock-processed fluid and the expanded fluid is called a contact surface. The conditions across the contact surface are constant pressure and constant velocity. The incident shock wave travels all the way along the test section until it reflects off of the end wall. Similarly, the expansion wave reflects at the end of the driver section. The reflected shock then interacts with either the contact surface and/or the reflected expansion wave (whichever it hits first).

Three-section shock tube operation is identical to two-section shock tube operation with the extra addendum that once the shock propagates through the driven section, it ruptures a second diaphragm separating the driven and test sections and the shock wave continues propagating into the test section.

2 GALCIT 6 inch shock tube

The GALCIT 6 inch shock tube (see Figure 1) has a 20-foot 4-inch (6.2 m) driver section, a 37-foot (11.3 m) driven section, and an 8-foot (24.4 m) test section. The driver and driven sections and the driven and test sections are each connected by a clamp. The clamps are used to position diaphragms between the sections. Once closed, the driver/driven section clamp can be pressurized by a hydraulic pump, typically up to 2500 psi. A plumbing schematic of the shock tube is given in the appendix. The 6-inch shock tube is equipped with piezoelectric pressure transducers located at various positions along the tube. The transducers are used to monitor the wave propagations by tracking the change in pressures. The 6-inch shock tube also has feedback control lights which should all be green before one can proceed with the experiment. These lights are connected to various valves, the clamp, and the hydraulic pressure line. A safety system controls the opening of the driver line solenoid valve. This valve is open only if the clamp is closed and the hydraulic

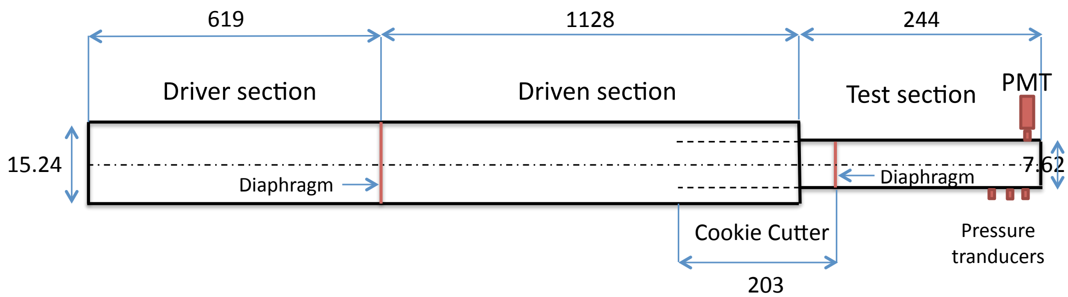

Figure 1: GALCIT 6 inch shock tube with test section–dimensions in cm.

pressure is above a threshold value of 1800 psi. A solenoid fixture is also located near the clamp handle. This fixture prevents one from opening the clamp if the driver section is pressurized. A solenoid-powered rod slides under the clamp handle when the pressure in the driver section is higher than 120 kPa.

Typically, shock tubes have flat end plates such that the shock wave will impact the end wall orthogonally and reflect normally. However, the GALCIT 6-inch shock tube has the test section attached that allows for conducting experiments measuring chemical kinetics.

3 Goal of the experiment

The goal of the experiment is to operate the shock tube in order to verify the shock tube equation, as well as to understand the influence of different parameters on the shock wave created. These parameters include the pressure ratio across the diaphragm, the thickness of the diaphragm, and the type of gases used. To aid in this understanding, we will use pressure transducers to monitor the shock and expansion waves and analyze them using distance-time diagrams.

After this, we will briefly investigate a phenomena known as shock wave bifurcation, which results from the interaction between the reflected shock wave at the end wall and the boundary layers formed behind the incident shock. This will be discussed in detail in section 13.

4 Operation of the shock tube

The shock tube is operated the following way. Once the appropriate diaphragm is chosen, it is put in place between the driver and driven sections. The hydraulic clamp is then closed and the hydraulic pump is activated, which pressurizes the clamp. The vacuum pumps should already be running and vacuum is done simultaneously in all sections in order to prevent the diaphragm from rupturing prematurely. The next step is to fill both sections with the desired gases, always keeping the pressure in the driver section slightly (about 10 kPa) higher than in the driven section so that the diaphragm is always bent in the same direction. Once the desired pressure in the test section is obtained, all the valves should be closed and the data acquisition system on the computer should be running. Then the driver section is slowly filled up until the diaphragm is pressed against the blades and bursts. The final step is to vent the shock tube. Remember:

- make sure you wear earphones when operating the shock tube
- always follow the checklist (in the order specified) when doing an experiment
- always keep the driver section to a higher pressure than the test section when filling

- never open the clamp if the tube is pressurized, always vent the tube before opening the clamp

5 Diagnostics

The diagnostics used in this experiment are piezoelectric pressure transducers (PCB model 113A21). They consist of a small diaphragm connected to a crystal. When a stress is applied to a piezoelectric material, it produces a small electric charge. This charge is converted to a voltage signal. Piezoelectric pressure transducers measure dynamic pressure. They behave like capacitive circuits. If the pressure applied does not change, the signal decays exponentially. The time constants for the transducers used in the 6 inch shock tube experiment are greater than 1 s, and the duration of the test is typically limited to 30 ms. Therefore, the change in pressure due to the exponential decay of the signal can be neglected. Pressure transducers need power supplies to operate. The power supplies have to be turned on before beginning any experiment. The outputs of the pressure transducers are connected to a data acquistion board which is linked to the computer. A LabView program is used to record the signals during the shots. The recording is triggered by the signal on the first pressure transducer PT1. Typical settings are specified below for the acquisition:

- PT_1 is set to channel 0, PT_2 to channel 1, PT_3 to channel 2 and PT_4 to channel 3.
- scanning frequency: 250 kHz
- acquisition period: 32 ms
- pretrigger scanning period: 2 ms
- trigger on PT_1, level 50 mV
- time limit for acquisition: 200 s (long enough to allow diaphragm burst)

The control panel uses 4 pressure gauges. The driven section has a 0-100 kPa Heise precision gauge, used to accurately fill up the section. It also has a Wallace and Tiernan 0-50 mm Hg vacuum gauge, used to check how good of a vacuum is obtained. The driver section has a 0-250 kPa Ashcroft pressure gauge, used in the simultaneous part of the filling. The last gauge is a 0-50 bar Heise precision gauge, used to measure the diaphragm burst pressure. All the gauge valves must be closed before firing, except for the 0-50 bar driver pressure gauge. Here are a few numbers to help you find your way with pressure units: 1 atm = 101325 Pa = 1.01325 bar = 760 mm Hg = 14.7 psi.

6 Test matrix

In the Ae104 experiments, the shock tube will be run with either room air or carbon dioxide as the driven gas and helium or nitrogen as the driver gas. We will not use a diaphragm between the driven and test sections, so the test section will act as an extension of the driven section. We will perform two test series which will result in a total of 22 shots.

6.1 Characterizing basic shock tube operation

Sixteen experiments will be performed to characterize basic shock tube operation. The driven gas in these experiments will be room air. Four different initial pressures of room air in the driven section will be tested: 25 kPa, 50 kPa, 75 kPa, and atmospheric (about 98 kPa). The thickness of the diaphragm, and consequently the burst pressure, will be varied between 6 and 12 mil (1 mil = 1 thousandth of an inch). Both driver gases, helium and nitrogen, are to be used. Thus a total of 12 shots (4 driven pressures x 2 diaphragm thicknesses x 2 driver gases) will be performed in this test series.

6.2 Shock wave bifurcation study

Shock wave bifurcation is discussed in detail in section 13, but the basics are described here. The effect results from an interaction between the boundary layer behind the incident shock and the reflected shock. The effect is stronger and occurs at a wider range of incident shock Mach numbers in gases with a low ratio of specific heats (γ). For this reason, strong shock bifurcation occurs more readily in carbon dioxide ($\gamma = 1.289$) than in air ($\gamma = 1.4$). As you will have observed from the characterization study, when helium is used as a driver gas the reflected expansion wave arrives very early in the test time compared to nitrogen. For this reason, shock bifurcation will not be easily observed if helium is used as a driver gas. Therefore nitrogen will be used as a driver gas for the entirety of this study.

Six experiments will be performed in this study. Two experiments will use room air as a driven gas at pressures of 20 and 30 kPa. The remaining four experiments will use carbon dioxide as a driven gas at initial pressures of 15, 20, 25, and 30 kPa. You will use 20 mil diaphragms for this set of experiments.

7 Safety considerations

During this laboratory exercise, you will be working with high-pressure gases to create shock waves. Accidental release of high-pressure gas into the laboratory will create shock waves that can cause significant hearing damage and possibly rupture your eardrums.[1] Furthermore, the velocity of the gas behind the shock wave is strong enough to launch nearby objects (such as tools and wall hangings) across the room, which could result in further injuries. The checklist exists to minimize the possibility of lab accidents. Headphones can save your hearing should accidental venting of high pressure gas occur as it only takes a relatively weak shock wave to damage your hearing. To give you an idea of the pressures you will be working with, here are some numbers to keep in mind. The numbers are given in terms of overpressure, which is the pressure in excess of atmospheric pressure. You eardrums can rupture at overpressures of 0.34 bar[2] and 50% of exposed eardrums rupture at overpressures of 1 bar[2]. Furthermore, lung damage can occur at overpressures in excess of 1 bar. The highest pressure experiment that you will perform will involve filling the driver to approximately 4.8 bar and the test section to 2 bar. Were you to accidentally open the shock tube with the driver at that pressure, Eq. 8 (discussed below) predicts that you would experience a Mach 1.3 shock wave with an overpressure of 0.9 bar. To make matters worse, the flow behind that shock wave will be moving at almost 150 m/s or 540 mph. It is critical that you observe the following rules while performing this experiment:

1. Follow the checklist at ALL times. You should place a checkmark next to each step immediately after you do it.
2. THINK about each step that you are about to perform. Don't blindly follow the checklist.
3. Wear ear protection whenever working with gas at a different pressure than ambient pressure. Headphones must be worn from the moment that the shock tube is evacuated until after the diaphragm clamp is opened after the experiment.

8 Gas Fill Bottles and Regulators

The gas used to fill the driver section during this laboratory will come from bottles filled with compressed gas. The bottles (nitrogen, helium, and carbon dioxide) are portable and located in the shock tube lab. All

[1] If catastrophic failure were to occur due to faulty operation or equipment failure, a blast wave would propagate into the experiment room. The most susceptible organ to blast damage are the ears which may be ruptured at overpressures of only 15 psi.[1]

the bottles are filled with pressures ranging from 207 to 340 bar (3000 to 5000 psi). Working with gas in that pressure range can be very hazardous (repeat the analysis performed in the previous section if you don't agree) and regulators are used to step the high-pressure gas down to a safer working pressure. The regulator has two pressure gauges; the one on the right (bottle) side corresponds to the pressure inside the bottle, so you can check how much gas is left in the bottle. With this particular configuration, never open both bottle valves and bottle line valves at the same time. The second gauge shows how much pressure is available on the shock tube side and is controlled manually by the regulator. Turn the handle until a reasonable pressure is obtained at the outlet of the regulator (typically 80 psi). Whenever the bottle needs to be changed, do not do it by yourself because mishandling high-pressure gas bottles can be very dangerous. Ask the instructor to do it or do it under the instructor's careful supervision.

9 Normal unsteady shock waves

A shock wave is a very thin region of the flow across which there is a rapid variation of state. It can almost always be idealized as a surface of discontinuity. This surface propagates into the fluid and all fluid properties—pressure, velocity, density—across it are discontinuous. The flow across a shock wave satisfies the conditions of balance for mass, momentum, and energy. Applying these conditions yields the following classical results for a normal shock wave in a perfect gas. The pressure jump, density jump, temperature jump, and velocity jump across the shock wave are given as well as the Mach number of the flow behind the shock:

$$\frac{P_2}{P_1} = 1 + \frac{2\gamma}{\gamma+1}\left(M_S^2 - 1\right) \tag{1}$$

$$\frac{\rho_2}{\rho_1} = \frac{M_S^2}{1 + \frac{\gamma-1}{\gamma+1}(M_S^2 - 1)} \tag{2}$$

$$\frac{T_2}{T_1} = 1 + \frac{2(\gamma-1)}{(\gamma+1)^2}\frac{(M_S^2-1)(1+\gamma M_S^2)}{M_S^2} \tag{3}$$

$$\frac{\Delta w}{a_1} = -\frac{2}{\gamma+1}\frac{M_S^2-1}{M_S} \tag{4}$$

$$M_2^2 = \frac{1 + \frac{\gamma-1}{\gamma+1}(M_S^2 - 1)}{1 + \frac{2\gamma}{\gamma+1}(M_S^2 - 1)} \tag{5}$$

where P_1 and P_2 are the pressures, respectively, before and after the shock, M_S is the shock wave Mach number, γ is the ratio of the specific heats of the gas, $a_1 = \sqrt{\gamma R T_1}$ is the speed of sound of the gas, $\Delta w = w_2 - w_1$ is the difference of the flow velocity across the shock, and M_2 is the Mach number of the flow behind the shock. The Mach numbers M_S and M_2 are defined as: $M_S = w_1/a_1$ and $M_2 = w_2/a_2$ where $a_2 = \sqrt{\gamma R T_2}$.

The previous analysis is useful for steady shock waves and is valid instantaneously for unsteady or moving shock waves. In the shock tube experiment, a moving shock wave is generated and a change of frame, as depicted in Figure 2, has to be performed in order to get the velocities in the lab frame. Travelling shock waves in normal fluids are compression waves and create a flow behind them in their direction of propagation.

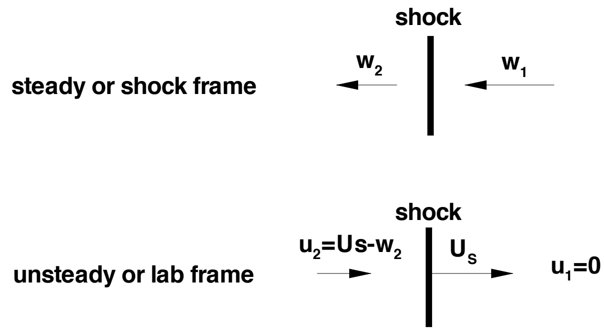

Figure 2: Steady and unsteady frames.

10 Expansion waves

Unlike shock waves, expansion waves are continuous changes in the state of a fluid. These waves propagate relative to the fluid at the speed of sound. They tend to spread and the change in properties across them is smooth. The fluid is expanded and accelerated in the direction opposite to the direction of propagation of the wave. Most importantly, expansion waves are isentropic, which is not the case for a shock. In the shock tube problem, you will have to deal only with expansion fans, which are series of waves starting from a common space-time location. The flow across an expansion fan can be solved using the method of characteristics. It uses invariants along characteristics going across the expansion fan. These invariants are for a perfect gas:

$$P = \frac{2a}{\gamma - 1} + u \qquad \text{along a } C^+ \text{ characteristic}$$
$$Q = \frac{2a}{\gamma - 1} - u \qquad \text{along a } C^- \text{ characteristic}$$

where u is the flow velocity, a is the sound speed, and γ the ratio of the specific heats of the fluid. These invariants have to be used on C^- characteristics for right-facing waves and on C^+ characteristics for left-facing waves. The latter case is illustrated in Figure 3.

Using this argument, the problem presented in the figure can be approached the following way: assume a_4, u_4, P_4, and u_3 are known, then

$$\frac{a_3}{a_4} = 1 - \frac{\gamma - 1}{2}\frac{\Delta u}{a_4} \tag{6}$$

where $\Delta u = u_3 - u_4$. Using the isentropic relationships across the waves then yields for a perfect gas:

$$\frac{P_3}{P_4} = \left(1 - \frac{\gamma - 1}{2}\frac{\Delta u}{a_4}\right)^{\frac{2\gamma}{\gamma-1}}. \tag{7}$$

This result is only valid for left-facing expansion waves. In the case of a right-facing expansion wave, the result would be similar except for a change of sign after the 1 in the equation. For a left-facing wave, Δu is obviously positive and the pressure will decrease across the wave, as expected.

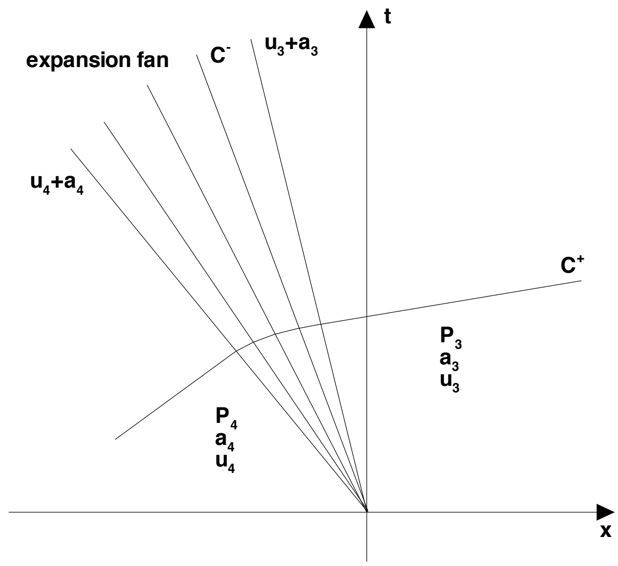

Figure 3: Left-facing expansion wave.

11 The shock tube equation

The shock tube problem starts with gas in the driven section at a pressure P_1, with a sound speed a_1 and a ratio of specific heats γ_1, and gas in the driver section at a pressure $P_4 > P_1$, with a sound speed a_4 and a ratio of specific heats γ_4. When the diaphragm breaks, a shock wave propagates into the driven section, changing the fluid form state 1 to state 2. At the same time, an expansion wave propagates into the driver section, corresponding to a change from state 4 to state 3. States 2 and 3 are located on either side of the contact surface (surface of discontinuity between the two gases). State 2 corresponds to the shock-processed fluid, while state 3 corresponds to the expanded fluid after the passage of the expansion wave. The conditions across the contact surface are constant velocity and constant pressure, i.e., $u_2 = u_3$ and $P_2 = P_3$. Figure 4 illustrates the problem physically and in terms of a distance-time diagram and figure 5 considers the effects of the test section diaphragm.

The flow properties in the different regions can be computed by using the conditions across the contact surface. The pressure and velocity jumps across the shock are known as a function of the shock Mach number. Similarly, the pressure and velocity jumps across the expansion fan can be determined. Matching the pressure and velocity across the contact surface yields the shock tube equation:

$$\frac{P_4}{P_1} = \frac{1 + \frac{2\gamma_1}{\gamma_1+1}(M_S^2 - 1)}{(1 - \frac{\gamma_4 - 1}{\gamma_1+1}\frac{a_1}{a_4}\frac{M_S^2-1}{M_S})^{\frac{2\gamma_4}{\gamma_4-1}}} \tag{8}$$

Therefore the shock wave Mach number M_S is a function of the pressure ratio P_4/P_1, the sound speed ratio a_4/a_1, and the ratios of the specific heats γ_4 and γ_1 of the driver gas and the test gas.

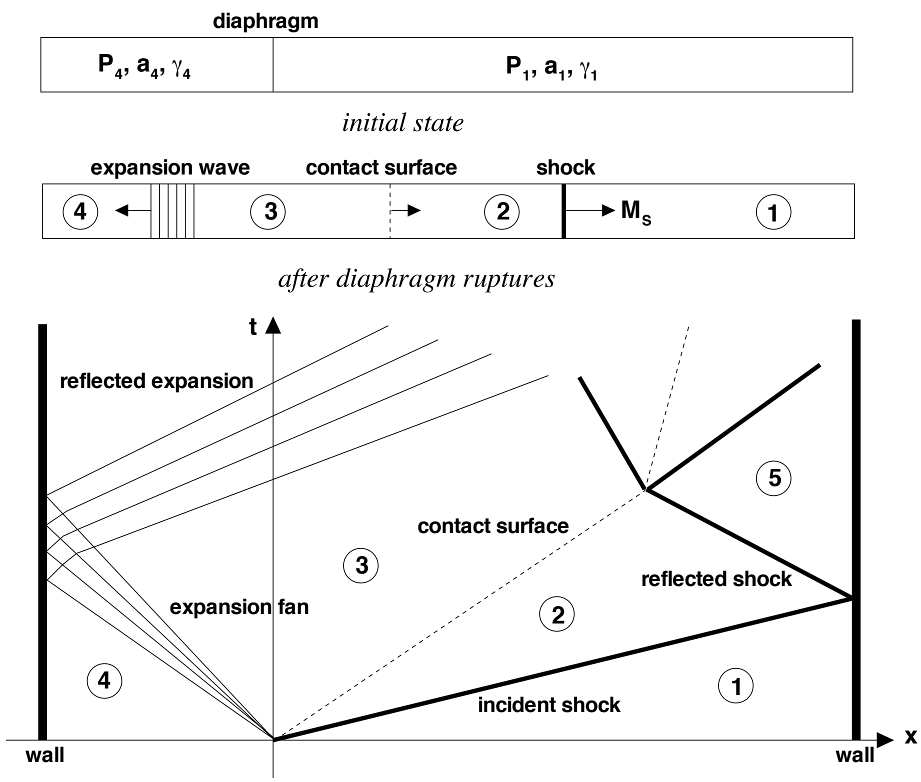

Figure 4: Shock tube experiment and wave diagram.

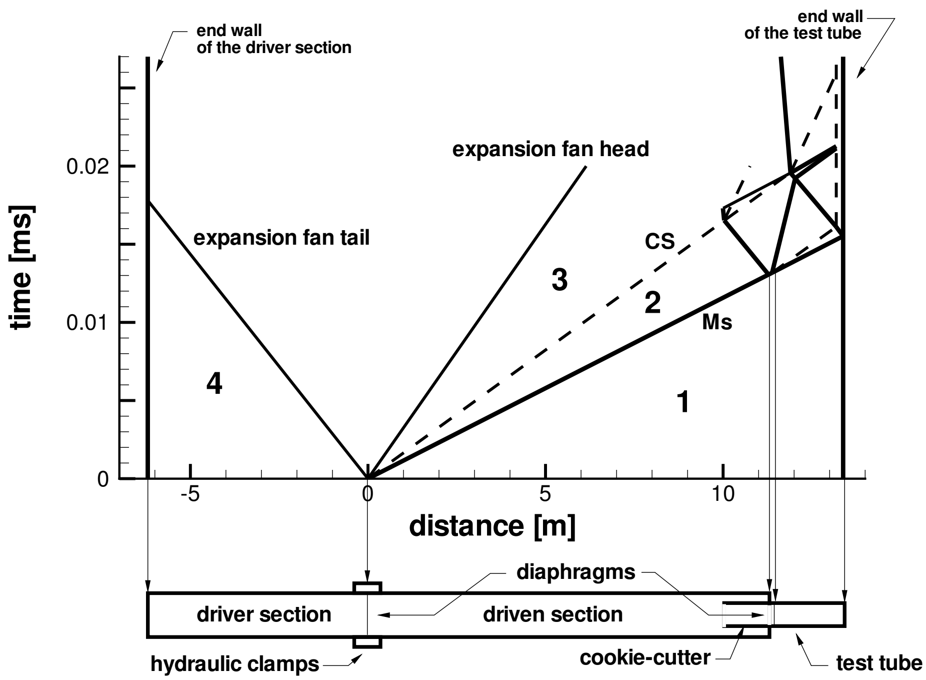

Figure 5: Wave diagram considering the test section.

12 Normal shock wave reflection

A shock wave reflects from a solid wall as a shock wave. Knowing the properties of the incident shock, it is possible to determine the properties of the reflected shock. The key boundary condition is zero velocity near the wall, i.e., behind the reflected shock. The region behind the reflected shock is typically called state 5. The pressure ratio across the reflected shock can be determined as a function of the incident shock pressure ratio:

$$\frac{P_5}{P_2} = \frac{(3\gamma - 1)\frac{P_2}{P_1} - (\gamma - 1)}{(\gamma - 1)\frac{P_2}{P_1} + (\gamma + 1)} \tag{9}$$

$$\frac{P_5}{P_1} = 1 + 2\left(\frac{P_2}{P_1} - 1\right)\frac{1 + \left(\frac{1}{2} + \frac{\gamma-1}{\gamma+1}\right)(M_S^2 - 1)}{1 + \frac{\gamma-1}{\gamma+1}(M_S^2 - 1)} \tag{10}$$

The reflected shock velocity is denoted u_R and the corresponding Mach number M_R. $M_R = \frac{u_R + u_2}{a_2}$ since the reflected shock propagates into a moving fluid corresponding to state 2. The reflected shock velocity and Mach number are given by the following equations:

$$\frac{u_R}{a_1} = \frac{1 + 2\frac{\gamma-1}{\gamma+1}(M_S^2 - 1)}{M_S} \tag{11}$$

$$\frac{M_R^2 - 1}{M_R} = \frac{a_1}{a_2}\frac{M_S^2 - 1}{M_S}. \tag{12}$$

13 Shock wave bifurcation

As we have previously discussed, the incident shock wave in the driven section sets up a steady flow behind it towards the end wall of the tube. Because of the no-slip condition, boundary layers form in this region of uniform flow behind the shock. The stagnation pressure in the boundary layer can be shown to only be a function of the shock Mach number and the ratio of specific heats of the driven gas [3]. The stagnation pressure depends on whether or not the Mach number of the flow in the boundary layer is supersonic with respect to a frame moving with the reflected shock. This Mach number is given by

$$M_{BL} = \frac{2(\gamma_1 - 1)M_S^2 + 3 - \gamma}{(\gamma + 1)M_S} \tag{13}$$

If $M_{BL} < 1$,

$$\frac{P_{stagBL}}{P_2} = \left(1 + \frac{\gamma_1 - 1}{2}\left[\frac{2(\gamma_1 - 1)M_S^2 + 3 - \gamma_1}{(\gamma_1 + 1)M_S}\right]^2\right)^{\frac{\gamma_1}{\gamma_1 - 1}} \tag{14}$$

If $M_{BL} > 1$,

$$\frac{P_{stagBL}}{P_2} = \frac{\left(\frac{\gamma_1+1}{2}\left[\frac{2(\gamma_1-1)M_S^2+3-\gamma_1}{(\gamma_1+1)M_S}\right]^2\right)^{\frac{\gamma_1}{\gamma_1-1}}}{\left(\frac{2\gamma_1}{\gamma_1+1}\left[\frac{2(\gamma_1-1)M_S^2+3-\gamma_1}{(\gamma_1+1)M_S}\right]^2 - \frac{\gamma_1-1}{\gamma_1+1}\right)^{\frac{1}{\gamma-1^1}}} \tag{15}$$

If the stagnation pressure in the boundary layer exceeds the pressure behind the reflected shock, P_5, then the reflected shock will proceed uniformly through the gas in regions 2 and 3. If, however, P_5 is greater than the pressure in the boundary layer, the boundary layer fluid is unable to pass into region 5 and collects in a "bubble" just behind the reflected shock. The shock then forms oblique "feet" to turn the freestream fluid in region 2 around the separated bubbles. This is shown in figure 6.

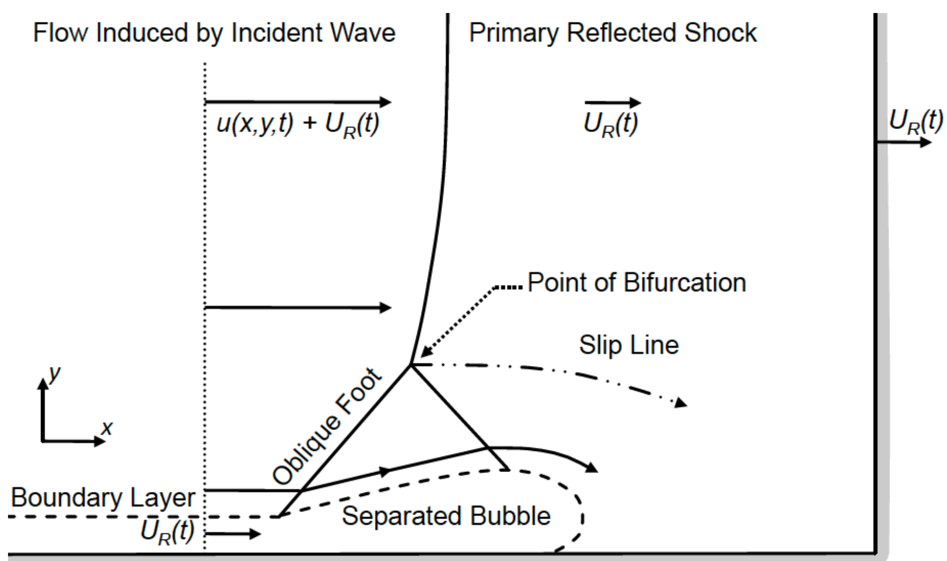

Figure 6: Diagram of shock wave bifurcation.

The pressure behind the reflected shock can be expressed as a ratio with P_2 so that the crossover points between where bifurcation will and will not occur can be determined analytically.

$$\frac{P_5}{P_2} = \frac{2\gamma_1}{\gamma_1 + 1}\left(\frac{2\gamma_1 M_S^2 + 1 - \gamma_1}{(\gamma_1 - 1)M_S^2 + 2}\right) - \frac{\gamma_1 - 1}{\gamma_1 + 1} \tag{16}$$

Curves for P_5 and P_{BL}, both normalized by P_2, are shown in figure 7 for values of γ of 1.289 (CO_2), 1.4 (air, N_2), and 1.667 (He, Ar). Bifurcation occurs in the region where $P_5 > P_{BL}$ [4].

A brief overview of bifurcation can be found in a 1956 paper by Herman Mark [3], and a more in-depth explanation of both bifurcation and other shock-boundary layer interactions in shock tubes can be found in a later paper by Mark [4]. Two more recent papers may also be useful if further explanation is needed [5, 6].

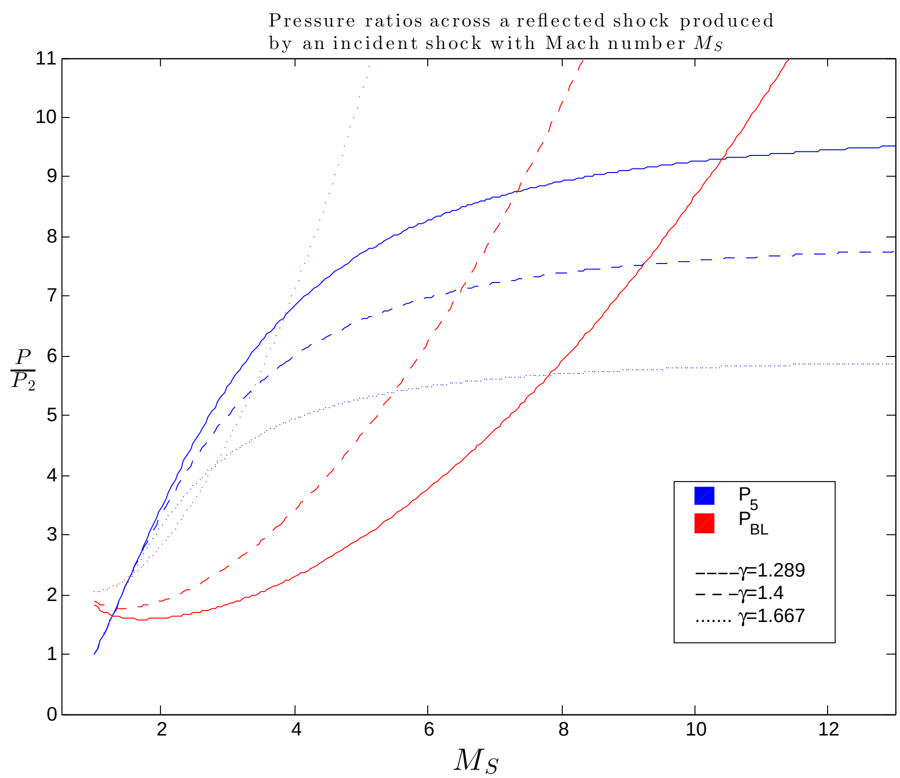

Figure 7: Plot showing region of possible shock wave bifurcation for 3 values of γ as a function of incident shock Mach number

14 Report requirements

The results of the experiment should be documented in a report. The report should include the following:

- description of the facility.
- table of run conditions, including results, i.e., the table should contain shot number, P_1, diaphragm thickness, driver gas, driven gas, M_S, P_2, P_4, and P_5.

- discussion on one non-ideal effect (see below).
- error analysis–qualitatively discuss what you perceive to be the principle errors in the experimental measurements, **also** provide a quantitative analysis of the experimental error in measuring the incident shock Mach number

For shock tube characterization study:

- comparison of theory and your measurements for P_4/P_1, P_2/P_1, P_5/P_1, u_R/u_S, versus M_S (experimental values). Also include a plot of M_S vs. P_4/P_1 for each driver gas used showing a theoretical curve and experimental data points with vertical error bars for M_S
- one pressure graph identifying shocks and expansion waves with a discussion.
- scaled x-t diagram for one run of your choice (including data points on your graph) showing the incident shock, the reflected shock, the contact surface, the expansion fan, the reflected expansion fan, and the first interaction.
- a brief discussion of the influence of initial pressures, driver gas, and driven gas on shock tube performance (shock Mach number and pressure after shock reflection).

Bifurcation study:

- a brief explanation of the shock wave bifurcation phenomenon (you may use this manual as a reference, but it should not be your only reference on this subject)
- two labeled pressure graphs, one showing bifurcation and one showing ideal shock reflection
- a discussion of the effect of incident shock Mach number on bifurcation
- Plot the growth rate of the bifurcation foot vs. incident shock Mach number for the CO_2 trials

The structure of the report typically follows the following outline: Abstract → Introduction → Theory → Non-ideal Operation → Experimental Setup and Procedure → Results → Discussion → Error Analysis → Conclusion → Table of Run Conditions. Those not familiar with shock tubes should review Thompson[7] or Liepmann and Roshko[8] for background material. When writing the section on non-ideal shock tube operation, briefly mention one or two phenomena that can cause shock tube experimental results to differ from the basic shock tube theory described above. Additionally, please go into detail on at least one of the following topics:

- Diaphragm time opening effects[9, 10].
- Predicting diaphragm burst pressure[9, 10].
- Real gas effects on shock tube performance for strong shocks[11].
- Boundary layer effects on the incident shock speed (effect of L/D)[12].
- Structure of shock front and thickness[13, 14].
- Curvature of shock wave due to boundary layer[15, 16, 17].
- Transition to turbulence of boundary layer behind the incident shock[18, 19].

A reference or two on each topic is provided. After reading the references listed for the selected topic, use the Web of Knowledge (accessible off the Caltech library webpage) in conjunction with the Caltech library to find an additional reference or two that is relevant to your topic. If you are not familiar with how to use the Web of Science, please ask a librarian or your TA.

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