AE3051 Experimental Fluid Dynamics

TRANSIENT MEASUREMENTS IN A SHOCK TUBE

Objective

In this set of experiments, piezoelectric transducers are used to measure pressures that change very rapidly with time. The pressure measurements are intended to help illustrate the operation and capabilities of a gas dynamics test facility called a shock tube, and to familiarize the student with moving shock and expansion waves.

Background

The Shock Tube

A shock tube is a device for generating gas flows or gas conditions that are difficult to achieve in other test devices. By its nature, the shock tube produces these conditions for a very short duration. In its simplest configuration, the shock tube consists of a long tube of constant area in which a diaphragm initially separates two bodies of gas at different pressures (Fig. 1a). The shorter section of the tube is at a higher pressure and is termed the *driver* section. The remaining longer part of the tube is at a lower pressure and is called the *driven* section of the tube. The gases in the driver and driven section need not be the same, and they can also be at different temperatures.

When the diaphragm is removed rapidly, for example by bursting it, a flow of short duration is established in the tube. A shock (compression) wave travels into the low-pressure driven section while a train of rarefaction (expansion) waves travels into the high-pressure driver section (see Fig. 1b). The flow regions induced between these waves are separated by an interface, or contact surface, across which the pressure and velocity are equal but the density and temperature are quite different (Fig. 1c-d). The contact surface also is the interface between the driver and driven gases, hence different gases may be present on either side of the contact surface as well.

As it propagates through the driven gas, the shock raises the temperature of the driven gas. The ideal dependence of the shock Mach number[1] on the initial conditions is illustrated in Fig. 2. As the pressure ratio across the diaphragm (P_4/P_1, see Fig. 1b for definitions) is increased, the shock Mach number of the advancing wave also increases. As compared to a situation where the driven and driver gas are identical, e.g., air and air, a shock with some given Mach number can be more easily produced (with a lower operating pressure ratio in the shock tube) by using a lighter driver gas, such as helium or hydrogen. Even larger shock Mach numbers may be achieved by heating the driver gas. In both cases, it is the increase in the speed of sound for the driver gas that causes the increase in the shock Mach number for a fixed pressure ratio, P_4/P_1.

After the incident shock reaches the end wall of the shock tube, a reflected shock travels back into the oncoming gases, in order to slow them down and nominally stopping them since they can not go through the endwall of the shocktube (see Fig. 1e). The Mach number of the reflected shock[2] is also a function, primarily, of the initial conditions in the shock tube. This is also illustrated in Fig. 2. Figure 3 is an expanded view of the shock Mach numbers for conditions similar to those of this experiment.

The temperature and pressure ratios, T_2/T_1 and P_2/P_1, across a moving shock wave as a function of shock Mach number are shown in Fig. 4. Recall that the temperature ratio is the ratio of two *absolute* temperatures, so that $T_2/T_1 = 5$ corresponds to a static temperature behind the moving shock wave of about 2660 R (2,200 °F) for a gas initially at room temperature (72 °F). Thus, one important application of the shock tube is the study of gases at very high temperatures, such as the temperatures found near stagnation regions in hypersonic flows. The shock tube is also used as an aerodynamic test facility in the subsonic, transonic and super-sonic speed regimes. While the pressures and shock Mach numbers attainable in the laboratory shock tube are much lower than those encountered in a typical shock tube test facility, the principles and problems are the same.

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[1]The shock Mach number is $M_S=u_S/a_1$, where u_S is the wave speed of the shock, and a_1 is the speed of sound in the *undisturbed, nonmoving gas* in the driven tube, i.e., M_S is the Mach number *relative* to the stationary driven gas. The speed of sound is given by $a=(\gamma R T)^{1/2}$, with $R_{air} = 1716$ ft^2/sec$^2 \cdot$R $= 288.7$ J/kg·K.

[2]The reflected shock Mach number is $M_R=(u_R+u_2)/a_2$, where u_R is the **speed** of the reflected shock (relative to the shock tube), and u_2 is the **speed** of the flow induced by the incident shock (also in the lab reference frame). Thus M_R is the wave speed *relative to the oncoming gas heated by the incident shock* (with sound speed a_2).

The performance of a shock tube, and the theoretical behavior shown in Figs. 2-4, may be calculated by methods discussed in AE 3450 relating to moving shock waves and expansion regions.[3] For example, the relationships described by Eqs. 1-7 (below) can be derived for our shock tube experiment, under the *assumptions*: **1)** the driven and driver sections of the tube are filled with the same gas, **2)** the gas is *thermally perfect* (and therefore obeys the equation of state $P = \rho RT$) and *calorically perfect* (has constant specific heat, independent of temperature), **3)** the shock Mach numbers are defined relative to the oncoming gas (see footnotes 1 and 2), **4)** all the waves are assumed to be one-dimensional, and **5)** except for the shocks, the flow is isentropic.

$$\frac{P_4}{P_1} = \frac{P_2}{P_1} \left\{ 1 - \frac{(\gamma-1)\left(\frac{P_2}{P_1} - 1\right)}{\sqrt{2\gamma\left[2\gamma + (\gamma+1)\left(\frac{P_2}{P_1} - 1\right)\right]}} \right\}^{\frac{-2\gamma}{\gamma-1}}. \tag{1}$$

$$\frac{u_2}{a_1} = \frac{2\left(M_S^2 - 1\right)}{(\gamma+1)M_S} \tag{2}$$

$$\frac{P_2}{P_1} = 1 + \frac{2\gamma}{\gamma+1}\left(M_S^2 - 1\right) \tag{3}$$

$$\frac{T_2}{T_1} = \left(1 + \frac{\gamma-1}{2}M_S^2\right)\left(\frac{2\gamma}{\gamma-1}M_S^2 - 1\right)\frac{2(\gamma-1)}{M_S^2(\gamma+1)^2} \tag{4}$$

$$\frac{M_R}{M_R^2 - 1} = \frac{M_S}{M_S^2 - 1}\sqrt{1 + \frac{2(\gamma-1)}{(\gamma+1)^2}\left(M_S^2 - 1\right)\left(\gamma + \frac{1}{M_S^2}\right)} \tag{5}$$

$$\frac{P_5}{P_2} = 1 + \frac{2\gamma}{\gamma+1}\left(M_R^2 - 1\right) \tag{6}$$

$$\frac{T_5}{T_2} = \left(1 + \frac{\gamma-1}{2}M_R^2\right)\left(\frac{2\gamma}{\gamma-1}M_R^2 - 1\right)\frac{2(\gamma-1)}{M_R^2(\gamma+1)^2} \tag{7}$$

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[3]For example, see James E. A. John, *Gas Dynamics*, 2nd edition, Prentice-Hall, Englewood Cliffs, 1984, pp. 63-87; or John D. Anderson, Jr., *Modern Compressible Flow*, 2nd edition, McGraw-Hill, Boston, 1990, pp. 64-69, 208-216, 237-238.

Measuring Devices

i) **Piezoelectric transducer** - This transducer looks not unlike a strain gage transducer in that it is a small cylinder with a diaphragm on one end. However, the diaphragm does not cover a cavity but instead rests on a small piece of quartz or crystalline material. When the quartz experiences a stress and strain due to the deflection of the diaphragm, the quartz produces a charge that is proportional to the strain, rather than a voltage that would be found in an unbalanced strain gage bridge. The diaphragm is flush-welded to the case and acts as a cover for the crystal rather than as a sensing element. The transducer is connected to an electrostatic charge amplifier that generates a high level, low impedance DC voltage output signal. The output signal is proportional to the strain, or thus the stress, applied. Here, the stress is induced by the pressure above the transducer. Piezoelectric transducers used for measurements in gas dynamics are typically 0.25 -0.50 inches in diameter and 1.5 - 2.0 inches long. Subminiature models are available that are less than 1 inch long and have a diaphragm only 0.10 inches in diameter.

Piezoelectric gages have a high output and are available for use at a wide range of pressures. Their foremost advantage is their time response. They have a natural frequency of over 250 kHz and a typical rise time of 2 μs. Thus they have the ability to follow rapidly changing (transient) pressures and are ideal in applications such as shock tubes, combustion chambers, engines, and explosions. Disadvantages of these devices include their sensitivity to temperature changes and to cross-accelerations (since such crystals also are used in accelerometers). They are not useful in measuring essentially constant pressures, since the charge will leak from the crystal if a constant load is applied for a long time; the discharge time is typically of the order of seconds.

ii) **Recording device** - The output of the piezo transducers must be recorded on a fast-response recorder in the form of pressure (or more precisely voltage output) versus time, where the entire time interval of interest typically is a small fraction of a second. Thus, the recording device must be sufficiently fast to capture and temporally resolve this single event experiment. Possible devices include oscilloscopes (either storage types or standard oscilloscopes equipped with a camera to record the cathode ray output), fast analog recorders (typically voltages written to an analog tape recorder), or transient digitizers such as those employed in computer data acquisition systems. For single event measurements associated

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with devices like the shock tube, the recording device must be triggered to acquire data during the very short duration of the experiment.

In this lab, data is acquired by a computer equipped with a 500 kHz analog-to-digital converter (ADC). The measurement recording is initiated by a "trigger" that instructs the acquisition system when the event has begun. Here, the trigger is supplied by a change in the signal on one of the recorded channels, specifically the first piezo device at station "A" (see Fig. 1a). The computer waits until the signal on this channel changes; the required change to initiate the data acquisition can be specified both by a threshold value (the *trigger level*) and by the direction or slope of the change, e.g., *rising* or *falling*. Because the data acquisition card employed here has 8 input channels, all four piezo outputs can be recorded during a single shock tube event.

PRELIMINARY

The following items must be turned in at the start of your lab session.

1. Based on a driver to driven pressure ratio (P_4/P_1) of 6, estimate the time required for the incident shock to travel the distance from station A to station D (see Fig. 1a for locations). For the same pressure ratio, estimate the time required for the reflected shock to travel from D back to A. You will use these calculations to help determine the settings for the data acquisition times.

PROCEDURE

1. The first step is to become familiar with the operation of the shock tube, its piping and valving. **With the tube open:**

   a. Check the water filter near the main air valve (along the wall); drain *if necessary*.

   b. Visually inspect the tube, the gages and joints for damage.

   c. Make sure air regulator is set to a maximum of 35 psi; this requires opening the main air pressure valve.

2. Determine the circuit diagram for the piezoelectric transducers and check the following.

a. Turn on piezoelectric power supply.

b. Check all 4 transducer channels for shorts using the meter on front of the piezo power supply.

c. Make sure that the output of each transducer is nearly zero by looking at it on an oscilloscope (or by grounding the center and outer connections on the BNC connectors, for example with a piece of wire).

3. Connect the transducers at **stations A, B, C and D** to the analog input **channels 0, 1, 2, 3** on the data acquisition system.

4. Familiarize yourself with the operation of the computer acquisition system VI (virtual instrument) interface.

a. Make sure the computer is set to **save data**.

b. Set the VI to record 4 **channels** (0,1,2,3).

c. Set the **trigger channel** to 0 (transducer "A")

d. Set the **scan rate** to 50,000 samples/sec (this represents the inverse of the time interval between data points on a given channel).

e. Set the **number of scans** to a value *such as* 5000 (the number of scans is the number of points acquired from each channel). For 5000 scans and a 50 kHz sampling rate, the total measurement time would be 0.1 sec (5000 samples / 50,000 samples/sec). Choose the numbers of scans to make sure that the total measurement time is *at least* long enough to capture the shocks (incident and reflected) on all the transducers based on the calculations you performed in the Preliminary section.

f. Set the ADC **voltage range** to 0-10 V.

g. Set the **trigger slope** to *rising* and the **trigger level** to 0.1 or 0.2 V (this means the system will start acquiring and recording data when the trigger signal is increasing and goes above 0.1 or 0.2 V).

2. Load the shock tube according to the procedure sheet located in the lab and/or the TA's instructions. The test pressures to be used are detailed in the **DATA TO BE TAKEN SECTION** below.

3. Just before firing the shock tube:

    a. Close valves to pressure gauges on shock tube control panel.

    b. Start computer acquisition system (you have ten seconds before computer times out).

    c. **Puncture** diaphragm with plunger.

    d. Save computer data to a file.

4. Observe the data on the computer screen. A total of at least four firings of the tube will be carried out.

DATA TO BE TAKEN

1. Make a sketch of the shock tube piping and valving and also of the instrumentation wiring.

2. Record the barometric pressure and room temperature. These will be needed to calculate absolute pressure and speed of sound.

3. The shock tube measurements should be carried out **at least** four times. For each shot, you will need to record the pressure in the driver and driven sections of the tube just before the diaphragm was broken. Be careful about units. The driver pressure gage is in psig; the driven pressure gage records inches of mercury *below* ambient pressure. The first two shock experiments should be performed with a driven pressure of -17 in. Hg and a driver pressure of 23 psig. For the third experiment, increase the driver pressure to 30 psig but still use a driven pressure of -17 in. Hg. For the fourth experiment, use as low a driven pressure as you can achieve, and use as high a driver pressure as you can (~33-35 psig?). Given extra time, feel free to try running the shock tube at other pressure ratios.

4. Calibration curves for all of the transducer are supplied.   The slope of the linear calibration curve (see the entry labeled **sensitivity** on the data sheet) must be read and recorded for all four gauges.

DATA REDUCTION

1. Calculate the pressure ratio P_4/P_1 (absolute pressures) for all your successful shock tube runs. Then, determine the theoretical value of the shock Mach number (from Figs. 2 or 3, or from Eqs. 1 and 3) for each shot.

2. Carefully measure the time interval between arrival of the incident shock wave at stations **A**, **B C** and **D**. Then, knowing the distance between these stations, calculate the resulting shock velocities. The incident shock Mach numbers may be found by dividing this value by the speed of sound of the air in the driven section. Assume the temperature of the undisturbed air in the driven tube is the same as the temperature of the air in the room.

3. Determine the theoretical value of the reflected shock speed (from Figs. 2, 3, and 4 or from Eqs. 4 and 5) for each shot.

4. Carefully measure the speed of the reflected shock by its travel time from station **D** to **C**, **C** to **B**, and **B** to **A**.

5. Determine the pressure rise P_2/P_1 experienced by the piezo transducers at stations **A**, **B** and **C** due to the incident shock. Also use the data to find the maximum pressure rise at all four stations **A**-**D**, which is the combination of two effects, the pressure rise P_2/P_1 of the incident wave and a second pressure rise P_5/P_2 caused by the reflected shock. Be sure to explain how you obtained these numbers from the piezo data.

RESULTS NEEDED FOR REPORT

1. Make a two-part figure showing the piping and wiring schematic for the shock tube as taken from your sketch.

2. Make a table containing the measured values of P_4 and P_1 (with units) and the ratio P_4/P_1 for all runs of the shock tube. Be sure to include the measured values of ambient pressure and temperature in the report.

3. Present plots of the piezo voltages acquired with the computer. Include output for all the transducers for a given shot on the same plot, and make separate figures for each shock tube run). (**Note:** while it is customary to plot data with symbols, this can be awkward if the spacing of the points on the graph is less than a reasonable symbol size. If this is true, you may wish to graph the data by drawing *curves that connect the points – however **do not** use curve fits*.) You may also wish to graph the data for one or more experiments more than one time; once for the complete time recorded on the computer and again for shorter times if you need to "zoom in" on interesting features of the data. For example,

you might want to graph just the times corresponding to when the "first" sensor sees the incident shock to the time the "last" sensor notices the passage of the reflected shock.

4. Make a table listing the theoretical value of the incident shock Mach numbers for each shot. Also include the measured incident shock velocities and Mach numbers from the various stations for each shot.

5. Make a table listing the theoretical values of the reflected shock speed for each shot. Also include the measured reflected shock velocities from the various stations for each shot.

6. Make a table listing the theoretical values of P_2/P_1 and P_5/P_1 for each shot. Also include the measured P_2/P_1, P_5/P_2 and P_5/P_1.
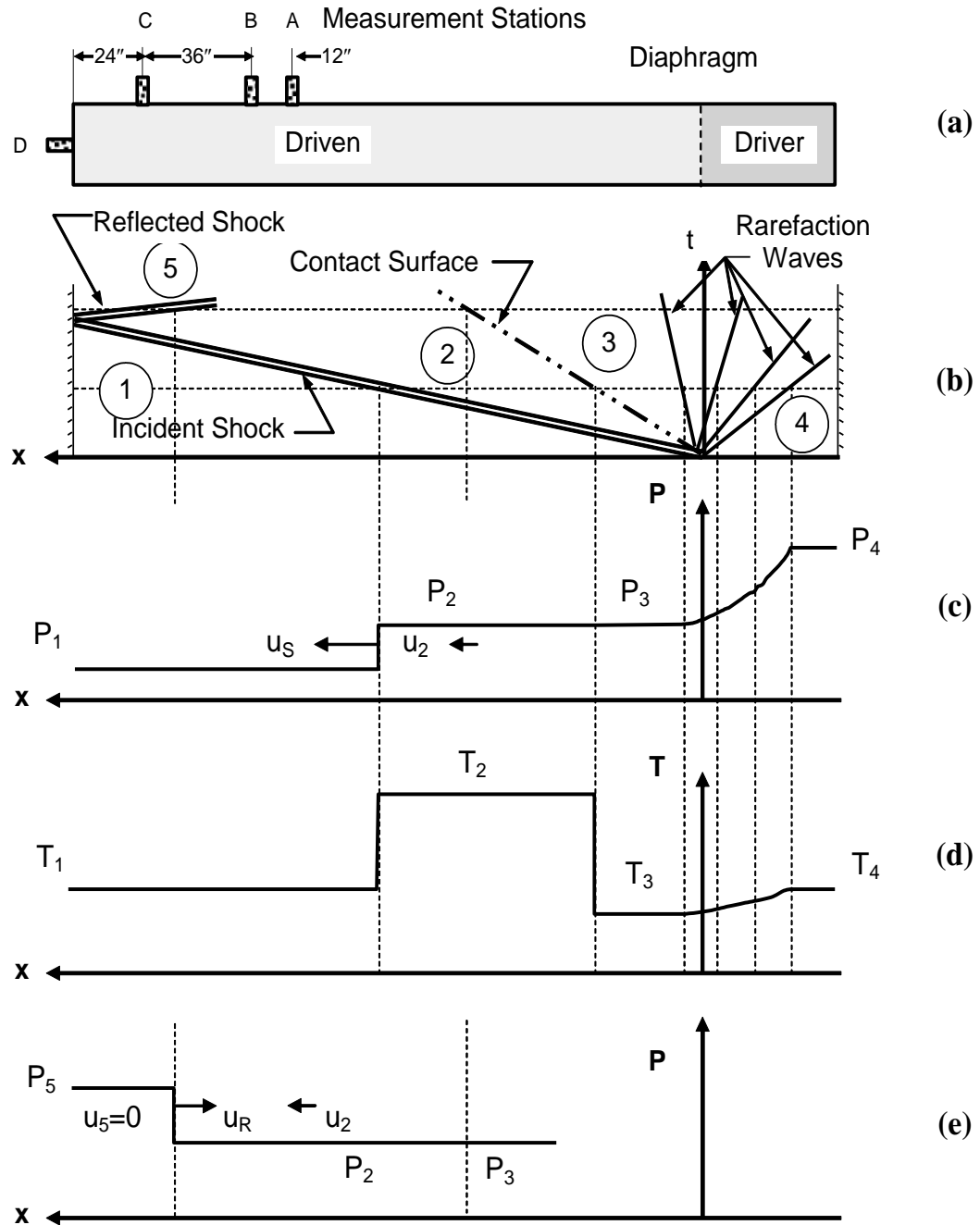
Figure 1. Shock tube and wave propagation: **(a)** shock tube schematic showing sensor locations; **(b)** x-t diagram showing ideal propagation of the (1-d) compression and expansion waves after the diaphragm bursts, and definition of regions 1-5; **(c)** pressure distribution in the shock tube at the fixed time indicated in (b); **(d)** temperature distribution for the same conditions as (c) ; and **(e)** pressure distribution at a later time, after the reflected shock has appeared.
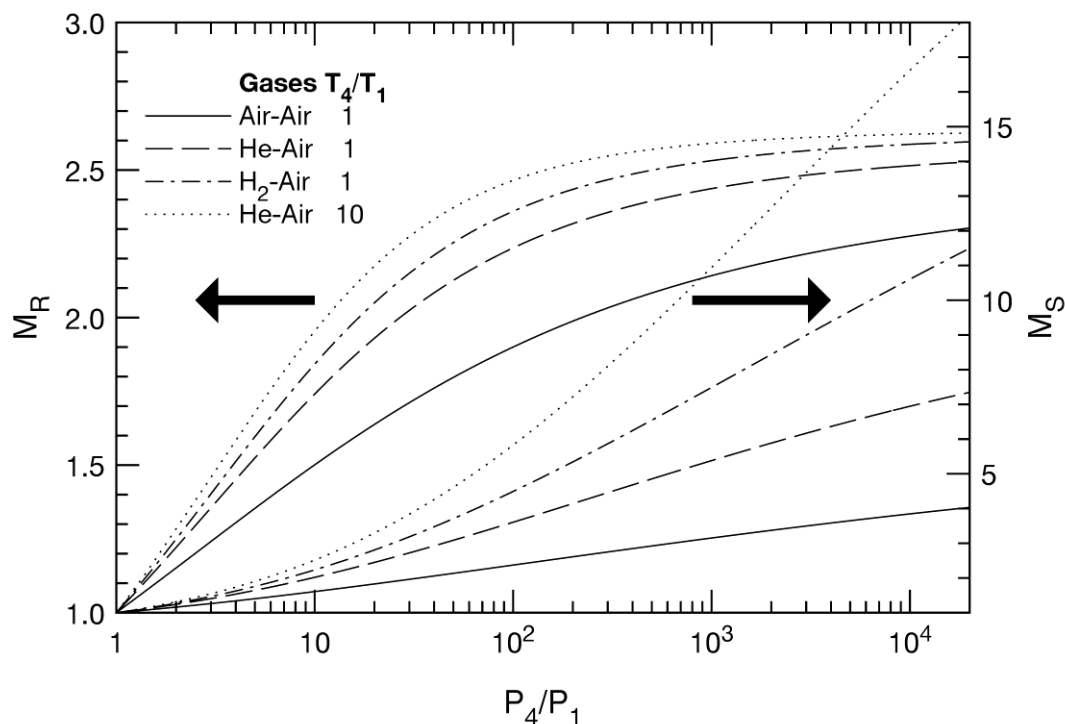
Figure 2. Variation of incident Mach number (M_S) and reflected shock Mach number (M_R) for various driver gas/driven gas combinations as a function of initial driver to driven gas pressure ratio (P_4/P_1).
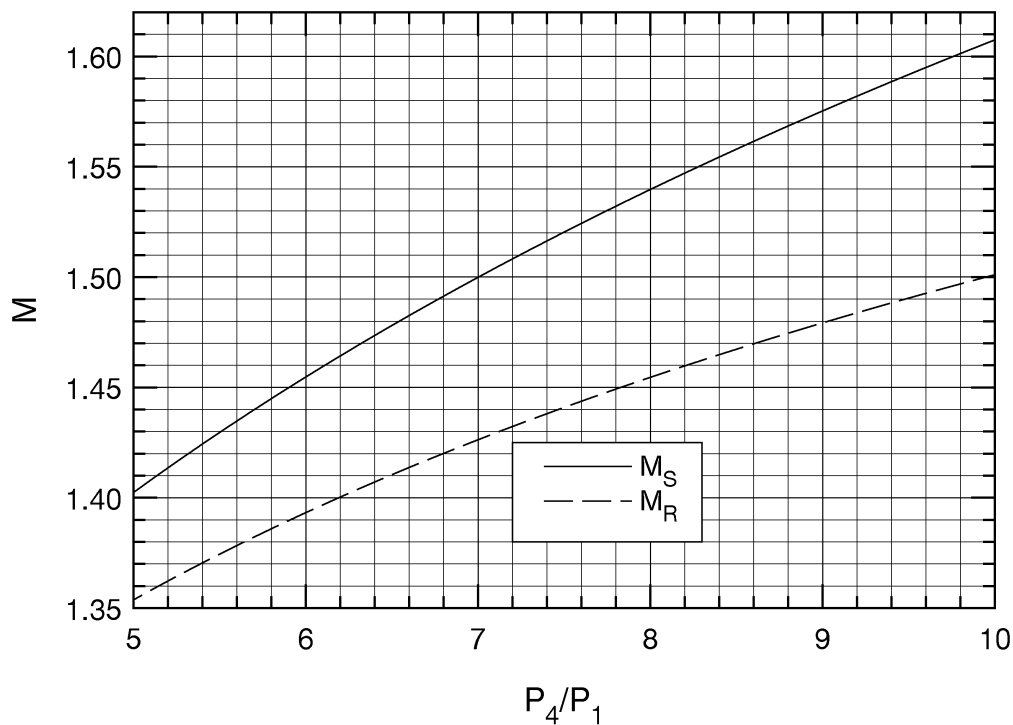

Figure 3. Variation of incident and reflected shock Mach numbers, for a shock tube with air as driver and driven gas and $T_4/T_1=1$, over a small range of P_4/P_1.
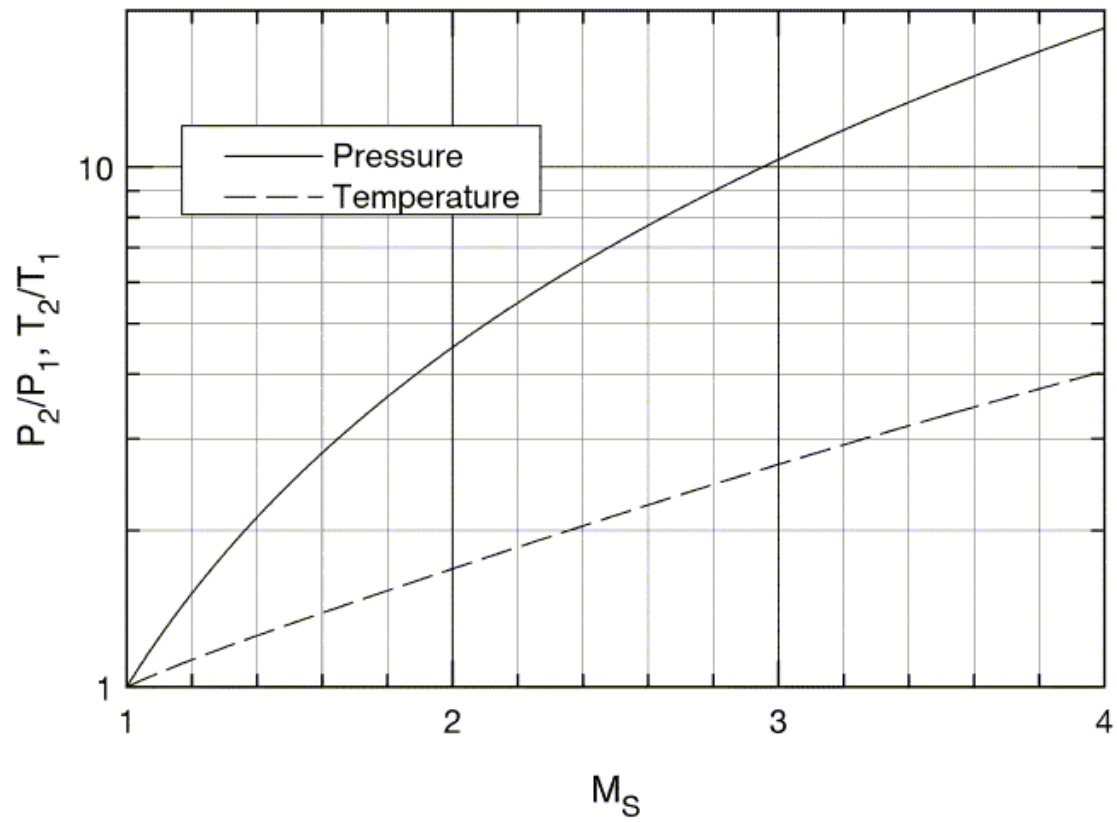
Figure 4. Shock pressure ratio, P_2/P_1, and shock temperature ratio, T_2/T_1, as a function of shock Mach number.