Pressure Response of a Pneumatic System

by

Richard A. Beier, PhD
rick.beier@okstate.edu
Mechanical Engineering Technology Department
Oklahoma State University, Stillwater

Abstract

This paper describes an instructive laboratory exercise for undergraduate students studying mechanical measurements and instrumentation. The experimental setup uses a pressure transducer, rubber tubing and a balloon to study the dynamic response of the assembled system as the balloon is punctured. The experiment demonstrates how the length of the tubing between the transducer and balloon changes the measured response at the pressure transducer. The results over a range of tube lengths illustrate how important the location of the pressure transducer becomes in the design of measurement systems. From the experimental data students can evaluate a frequency and a damping parameter to characterize the system for each tube length.

I. Introduction

The dynamic behavior of sensors is a typical topic in most mechanical measurements (instrumentation) undergraduate courses in both engineering and engineering technology programs. This paper describes an experiment to illustrate the dynamic behavior of a pressure transducer and its sensing line. The experiment illustrates how the sensing line affects the dynamic response of the transducer. The experiment is easy to set up with off-the-shelf components. Together the sensing line and transducer behave as a second-order system [1, 2], which is characterized by a natural frequency and a damping parameter. Both of these parameters are evaluated from the experimental results given in this paper. Pressure transducers, accelerometers and load cells typically behave as second-order systems, which can be idealized as an analogous spring-mass mechanical system.

Safety or accessibility issues in industrial applications may require a pressure transducer to be located at a distance from a pressure vessel or the desired location where pressure should ideally be measured. For instance, the transducer may be placed away from the vessel to give a person accessibility to service the sensor or the conditions nearer to the vessel may be hazardous. A sensing line or tubing connects the transducer to the ideal measurement location as illustrated in Figure 1. The resonance frequency of the pneumatic line becomes important, if a dynamic measurement is made through the line. The pressure transducer system can accurately measure input pressure signals with frequencies less than about 1/10 the resonance frequency of the sensing line [3]. Thus the sensing line directly impacts the working range of the pressure transducer system.

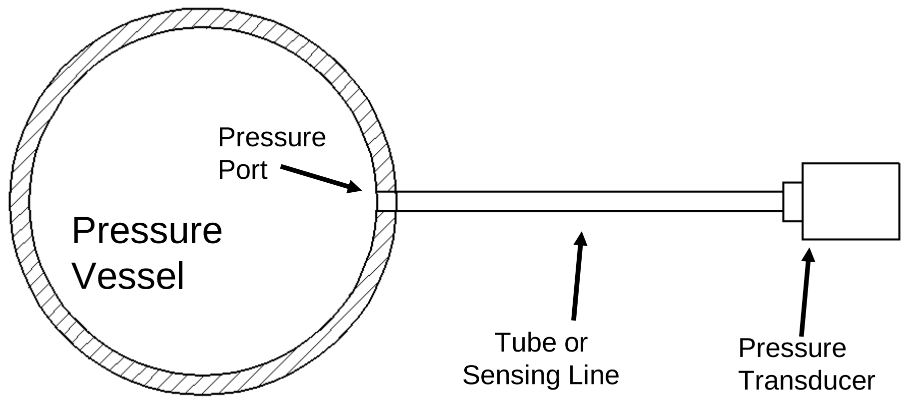

Figure 1. Pressure transducer installed with tubing.

After setting up and performing the experiment, students can gain insights by comparing mathematical models from the technical literature to their experimental results. Wheeler and Ganji [1] and Doebelin [2] have summarized some simple models showing the dynamic effects of the sensor line on the pressure transducer's response. Hougen et al. [4] develop a simplified model for a pneumatic transmission line, which applies to the geometry of this experiment. Their model uses concepts developed earlier by Schuder and Binder [5].

II. Experimental Setup and Procedure

In the experimental setup (Figure 2) the pressure transducer is connected to rubber tubing with an inflated balloon on the other end of the tubing. When the balloon is punctured, a sudden drop in pressure occurs at the tube outlet. If the tubing is sufficiently long, the tubing acoustically resembles an organ pipe after the balloon is punctured. The pressure transducer measures the dynamic acoustic response, which is recorded by a computer data acquisition system.

Different types of pressure transducers are available from vendors. One should choose a transducer with a sufficiently fast dynamic response to measure up to 1000 Hz oscillating pressures. For the experiments describe in this paper, the chosen pressure transducer (Validyne Engineering Corp., Model DP15-32-N-1-S-4-A) measures differential pressure across a diaphragm that is clamped in the middle of the upper and lower casing halves of the transducer (Figure 3). Pick-off coils within the casing detect the diaphragm's deflection by an imposed differential pressure across input ports on each side of the transducer. The port on the opposite side of the tubing is open to atmospheric pressure. The diaphragm in the transducer has a pressure range of 0 to 55 inches of water. A threaded fitting is connected to each pressure port (1/8-27 NPT female) with a barbed end for connection to a rubber hose.

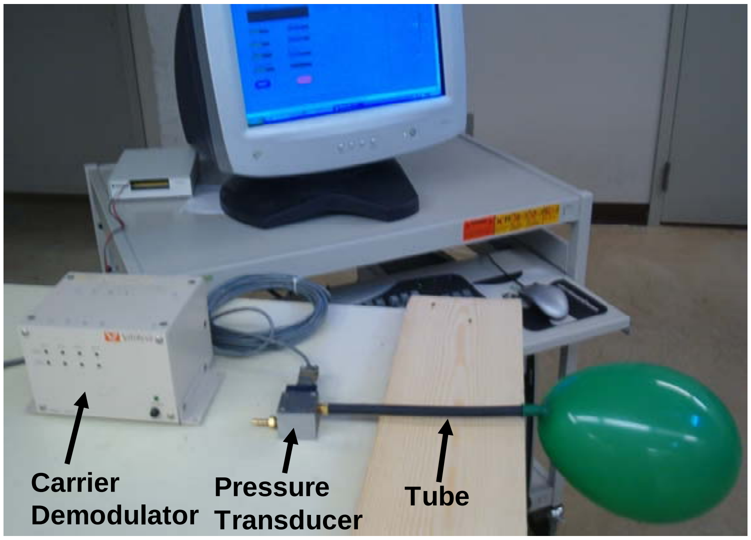

Figure 2. Experimental setup.

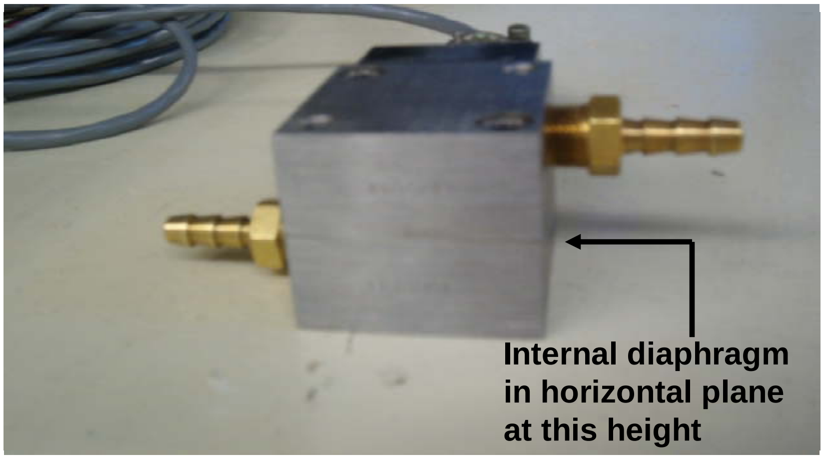

Figure 3. Pressure transducer and fitting for tube.

The transducer is connected electrically to a carrier demodulator (Validyne Engineering Corp. Model CD280), which provides power, carrier signal, and signal conditioning for the transducer. The output signal of the carrier demodulator is a +/- DC voltage that is linear with applied differential pressure across the transducer. This output signal is connected to a PC data acquisition system.

The procedure for each experiment is simple. A rubber hose (ID 0.225 inches; OD 0.420 inches) is attached to the positive pressure port on the transducer. If the hose is long, masking tape is used to tape it to a table so that it remains straight. The end of the hose extends over the edge of the table, and an inflated balloon if placed on the end of the hose. A round 7-inch balloon from a discount store fits snugly over the end of the tube and remains in place without any clamping. The computer data acquisition system is started and the balloon is punctured with a sharp needle or pin. To minimize unwanted noise one should use a very sharp needle and restrain the movement of the inflated balloon with one's hand. The sampling rate of the data acquisition system is 10,000 samples per second for hoses over 25 inches and 100,000 samples per second for shorter hoses. Multiple runs of the experiment use hose lengths ranging from 1 inch to 99 inches.

III. Results and Discussion

The puncturing of the balloon applies a step drop in pressure at the end of the tube. A typical response of the pressure transducer in Figure 4 shows a damped oscillation or ringing for a tube length of 10 inches. The response is consistent with a second-order system in mechanical measurement or instrumentation textbooks [1, 2]. Such a response can be characterized by two parameters: a frequency and damping constant.

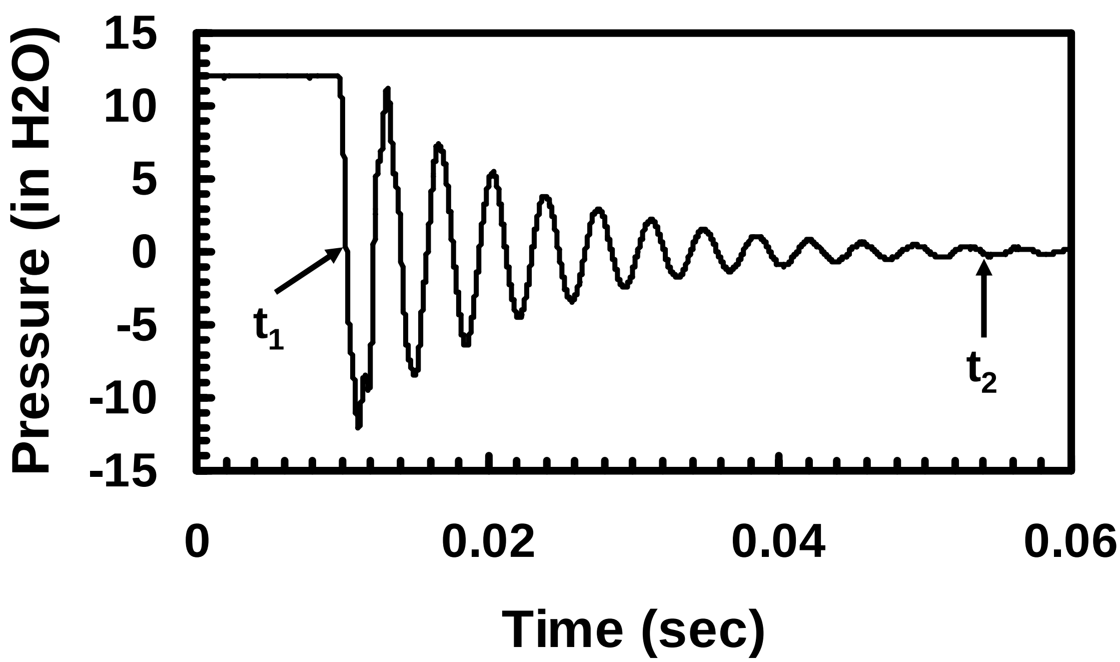

Figure 4. Damped oscillating response of pressure transducer.

The oscillation has a single frequency, which can be evaluated by counting zero crossings within a selected time window. The ringing frequency, f, is evaluated as

$$f = \frac{N_{zc} - 1}{2(t_2 - t_1)} \quad (1)$$

where

N_{zc} = number of zero crossings in window
t_1 = starting time of window
t_2 = ending time of window

The values of t_1 and t_2 are chosen to coincide with zero crossings as illustrated in Figure 4. Alternately, one may apply Fourier analysis [1] to the output, but this is not necessary here because only one frequency is present in each experimental run. For a single frequency the zero-crossing method is adequate.

The frequency of the dynamic response of the pressure transducer has been determined over a range of tube lengths as plotted in Figure 5, where each data point corresponds to a different tube length. For long tube lengths the frequency corresponds reasonably close to lowest natural frequency of the air column in the tube (closed at one end) given by

$$f_{tube} = \frac{v}{4L} \quad (2)$$

where

f_{tube} = lowest natural frequency of tube (Hz)
v = speed of sound (ft/sec)
L = length of tube (ft)

The dashed curve in Figure 5 corresponds to Equation 2, which is given in undergraduate physics textbooks [6]. The speed of sound for air, if treated as an ideal gas, is given by

$$v = \sqrt{\gamma \, R \, g_c T} \quad (3)$$

where

γ = specific heat ratio for air (1.4)
R = gas constant for air (53.35 (ft-lbf)/(lbm-ºR))
g_c = unit conversion constant (32.2 (lbm-ft)/(lbf-sec^2))
T = air temperature (534 ºR)

For the air temperature in this experiment of 74 ºF (534 ºR) the speed of sound is 1130 ft/sec.

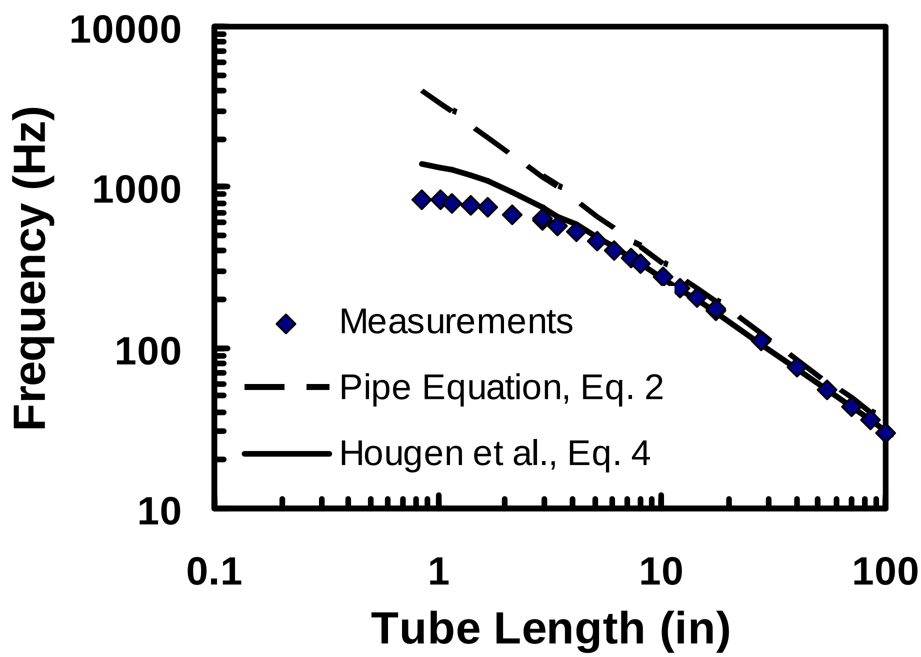

Figure 5. Frequency of pressure transducer response for different tube lengths.

As the length of the tube becomes shorter the data depart from the straight line (Equation 2) in Figure 5, because the effect of the volume of air in the chamber of the transducer becomes more significant and lowers the resonance frequency of the system. Wheeler and Ganji [1] explain the gas in the transducer chamber responds like a spring acted on by the mass of gas in the sensing line. The diaphragm undergoes deflection, but its displaced volume is very small compared with the chamber volume. Viewed as a spring, the diaphragm is much stiffer than the compressible gas in the chamber and the change in volume of the cavity associated with the deflection of the diaphragm is negligible.

Hougen et al. [4] treat the sensing-line air and the air in the pressure transducer chamber together as a second-order system. Based on their analysis the natural frequency of the system is

$$f_s = \frac{C}{2\pi L\sqrt{0.5 + \dfrac{V_t}{V_s}}} \tag{4}$$

where

V_t = volume air in transducer chamber (2.42×10^{-5} ft^3)
V_s = volume of air in tube (ft^3)

Actually, the threaded fitting installed into the pressure port of the transducer adds to the effective volume of the transducer cavity, because the air sees a small opening between the threaded side of the fitting and the barb side where the tube is attached (Figure 3). Thus, the value of V_t includes this added volume on the threaded side of the fitting. Equation 4 matches the data in Figure 5 within 5% for tube lengths greater than 5 inches.

For shorter lengths the discrepancy between Equation 4 and the measurements increases. One possible reason for the discrepancy is the mathematical approximations made by Hougen et al. [4] break down at higher frequencies. Also the pressure transducer actually has two cavities: 1) an entrance cavity where the fitting connects to the rubber hose and 2) an inner cavity where the actual diaphragm resides. The application of the model combines the volume of these two cavities into a single cavity.

To characterize the damping of the oscillation, the normalized amplitudes of successive peaks in Figure 4 are plotted on the vertical axis (logarithmic) in Figure 6. The amplitude of each peak is divided by the amplitude of the first peak to calculate the normalized amplitude. The cycle number for each peak is shown on the horizontal axis. The values of the peaks fall on a linear trend, which is consistent with viscous damping [7]. To quantify the damping a logarithmic decrement, δ, is calculated from either peaks or troughs,

$$\delta = -\frac{1}{n}\ln\left(\frac{x_n}{x_0}\right) = -\frac{1}{n\log(e)}\log\left(\frac{x_n}{x_0}\right) = -\frac{2.303}{n}\log\left(\frac{x_n}{x_0}\right) \qquad (5)$$

where

x_0 = the magnitude of the first peak (trough)
x_n = the magnitude of the nth peak (trough)

Here ln(x) represents the natural logarithm of x, and log(x) represents the common logarithm of x.

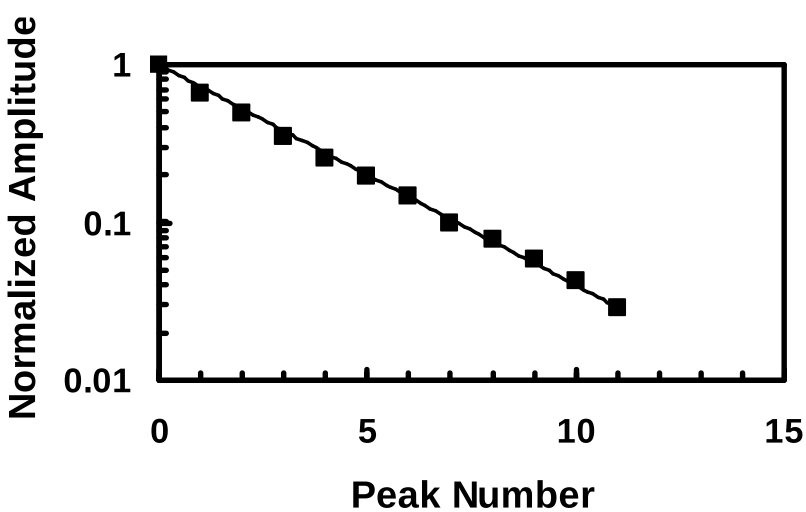

Figure 6. Normalized amplitude of successive peaks in Figure 4.

To evaluate the value of δ from the slope in Figure 6, one needs to rearrange Equation 5 to give

$$\log\left(\frac{x_n}{x_0}\right) = (-2.303\ \delta)\ n \tag{6}$$

Thus, the slope in Figure 6 is (-2.303 δ) or

$$\delta = -0.4343\ (\text{slope}) \tag{7}$$

The logarithmic decrement has been determined from experiments over a range of tube lengths. The results in Figure 7 show the logarithmic decrement has a minimum of about 0.3 between tube lengths of 3 to 10 inches, but δ increases for shorter and longer tubes lengths. As explained by Wheeler and Ganji [1], the fluid-resistance at the sensing-line wall is not well understood for oscillating flows, and theoretical predictions to quantify the damping parameter have shortcomings. In this experiment the inner wall of the fitting is different from the rubber tubing and this difference may become significant at short tube lengths.

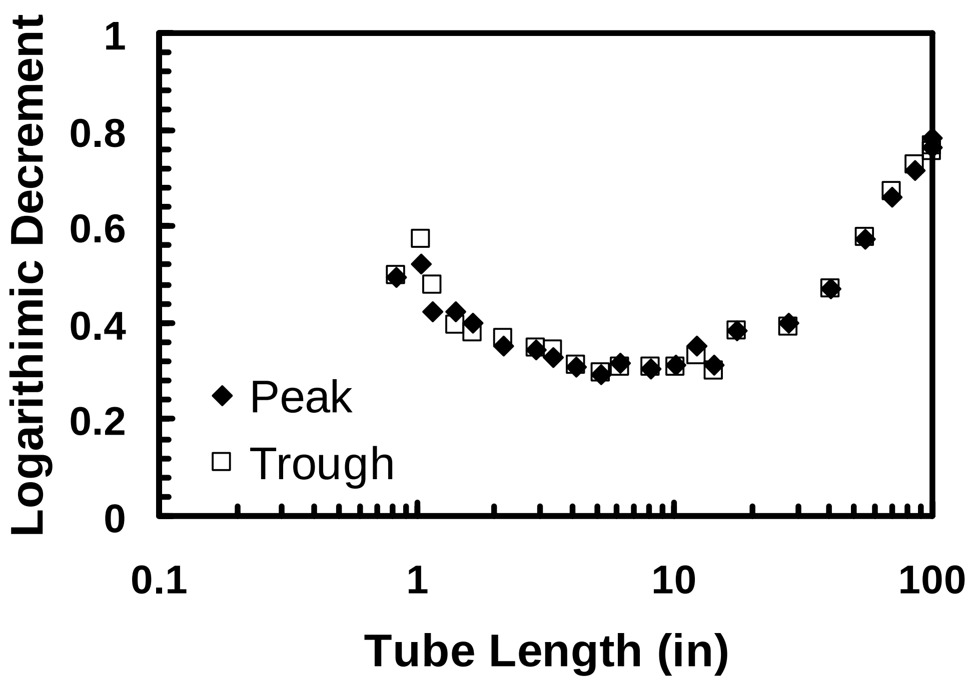

Figure 7. The logarithmic decrement of damped oscillations for different hose lengths.

The very simple pneumatic system consisting of a pressure transducer, rubber tubing and balloon is a good experimental setup for students to learn how important a transducer's location influences its recorded output. The system generates a damped oscillating response that changes with the length of tubing between the transducer and the punctured balloon. After performing a set of experiments students can analyze the data to estimate frequency and damping constants for the system. The system behaves as a second-order system, which is a common topic in mechanical instrumentation courses.

For long tube lengths the lowest natural frequency of the tube dominates the output response of the pressure transducer. For tube lengths less than 10 inches the air volume in the cavity of the pressure transducer becomes more significant and lowers the resonance frequency of the system. Students can evaluate these effects by comparing Equations 2 and 4 with their experimental results.

The damped oscillating response is consistent with viscous damping as illustrated in Figure 6. Using Equation 7 students can quantify a damping parameter and study how damping changes with tube length.

References

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