

11.3.5: Signal Conditioning – Vibration Measurement

Overview:

When making time-varying measurements, the sensor being used often has lower than desired sensitivity and a higher than desired noise level. *Frequency selective circuits* are therefore often used to *condition* the sensor's output signal. *Low-pass filters*, for example, can be used to increase the sensor's low-frequency sensitivity while reducing the high-frequency noise components in the sensor output signal.

In this lab assignment, we will condition the output from a piezoelectric sensor with a low-pass filter. Our goal will be to design a filter to amplify the frequencies of interest – those frequencies below the fundamental vibration frequency of the beam – and suppress higher-frequency components of the signal, which we will interpret as noise.

Before beginning this lab, you should be able to:

- Perform frequency-domain analysis of electrical circuits
- Represent sinusoidal signals in phasor form
- Analyze operational amplifier based electrical circuits

After completing this lab, you should be able to:

- Use a piezoelectric sensor to measure the vibration of a cantilever beam.
- Estimate the fundamental frequency in a measured signal
- Design and implement a first order low-pass signal conditioning circuit
- Measure the frequency response (gain and phase) of a system

This lab exercise requires:

- Analog Discovery module
- Diligent Analog Parts Kit
- Digital multimeter (optional)

Symbol Key:



Demonstrate circuit operation to teaching assistant; teaching assistant should initial lab notebook and grade sheet, indicating that circuit operation is acceptable.



Analysis; include principle results of analysis in laboratory report.



Numerical simulation (using PSPICE or MATLAB as indicated); include results of MATLAB numerical analysis and/or simulation in laboratory report.



Record data in your lab notebook.

1. Piezoelectric Sensor Vibration:

The *dynamic response* (or time-varying response) of a mechanical system can be extremely important in the determination of the structural loads in the system. The dynamic response can often be the dominant contributing factor in the stresses in the structure and, as such, can be the primary factor in a structure's failure. The famous Tacoma Narrows bridge failure was caused by the bridge's dynamic response to wind loads. A loading condition is considered to be dynamic if the loading condition changes relatively rapidly compared to how quickly the structure can respond to the load. "Plucking" a guitar string or striking a tuning fork, for example, are dynamic loading conditions, since they set up responses which persist much longer than the actual application of the input.

A system's dynamic response is often interpreted in terms of *vibration*. Vibration is essentially an oscillatory mechanical displacement. In our guitar string and tuning fork examples above, it is apparent that the systems oscillate as a result of the applied input. In general, structural vibrations do not consist of a single, sinusoidal, frequency component. (The tuning fork example is an exception to this rule; tuning forks are designed to vibrate at a single frequency, thus producing a pure auditory tone.) If multiple frequency components are present in a system's dynamic response, these frequency components are generally described in terms of the system's *modes* of vibration. The modes of vibration of the system are the *independent* ways in which the natural response of the system can vibrate. Some modes will be more important than others, from the standpoint of their contribution to the overall dynamic displacement of the system; the most important modes are often called the *dominant* or *fundamental* modes. In the guitar string example above, there are a number of frequencies which contribute to the sound we hear from the guitar (the sound is not a pure tone); these contributions are due to the different vibrational modes of the guitar string.

Vibrations are often measured using piezoelectric sensors. Piezoelectric devices produce a voltage when they are deflected. By bonding the device to a vibrating system, the output voltage from the sensor will indicate the vibration levels the system is experiencing. In this part of the lab assignment, we will induce a vibration in the piezoelectric sensor itself and measure its response. This data will be used to estimate the fundamental mode of vibration of the sensor. The design of the low-pass filter we will use later as our signal conditioning system will be based on this fundamental mode of vibration.

Pre-lab:

Read the material in Appendix A relative to piezoelectric sensors.

Lab Procedures:

- a. Connect the leads of one channel of your oscilloscope to the sensor contacts (the tabs protruding from the piezoelectric sensor). "Flick" the sensor and verify that you are receiving a signal on the oscilloscope from the sensor. Adjust the time and amplitude scales on your oscilloscope until the oscilloscope displays what you feel is a reasonable representation of the sensor's deflection as a function of time on the oscilloscope.

DEMO

- b. Demonstrate operation of your circuit to the TA and have them initial the appropriate page(s) of your lab notebook and the lab worksheet.

- c. Verify that the piezoelectric sensor provides no steady-state response to a constant input. To do this, use the oscilloscope to monitor the output voltage from the sensor as above. Bend the sensor to a constant deflection (bend it and leave it bent) and monitor the output of the sensor on your oscilloscope. The sensor output voltage should return to zero volts, even though the sensor is still deflected. Comment on your results in your lab notebook. Include a qualitative discussion as to what frequencies the sensor responds to. What type of frequency-selective circuit does the sensor resemble (low-pass, high-pass, band-pass, etc.)?
- d. Measure the natural response of the sensor. To do this, hold the end of the sensor to which the leads are attached and deflect the other end of the sensor slightly. This corresponds to an initial condition on the sensor deflection. Release the sensor tip suddenly, this allows the sensor to respond to this initial condition. Since no external forces act on the sensor after it is released, this corresponds to the natural response of the sensor.

ANALYSIS

DATA

Acquire the natural response waveform on your oscilloscope. (You may wish to use the **run/stop** button or the **single sequence** capability on your oscilloscope to do this. **Run/stop** will require you to **manually stop the oscilloscopes data acquisition when the signal is acquired**; single sequence will use the oscilloscope trigger to acquire the waveform) Save the waveform to a file.

ANALYSIS

Estimate the dominant frequency in the signal and note it in your lab notebook. (Note: this will correspond to the fundamental mode of the sensor; this *mode shape* consists of the sensor vibrating in a “shape” that we typically associate with the motion of a swimming pool diving board, as shown in Figure 1.) Also note that the recorded waveform contains frequency components other than the dominant frequency; the signal is not a pure sinusoid with a single frequency.

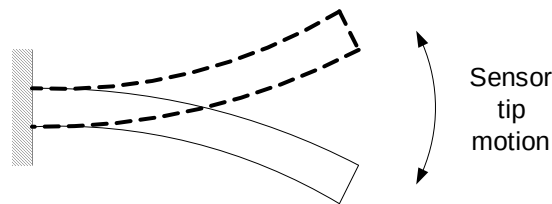


Figure 1. Dominant mode shape for sensor vibration (side view).

2. Signal Conditioning Circuit:

The voltage output from many measurement systems suffers from two primary shortcomings:

1. The output voltage can be noisy.
2. The sensitivity of the output voltage can be lower than desired

To overcome the above problems, we will design and implement an electrical circuit to *condition* the output voltage from the sensor before displaying the signal on the oscilloscope. The circuit we will use performs two primary functions, each of which is intended to compensate for one of the above shortcomings. The circuit will:

1. *Low-pass filter* the output signal from the sensor. This will reduce the high-frequency noise in the sensor's output voltage.
2. *Amplify* the output signal from the sensor. This will increase the sensitivity of the overall measurement.

We will implement the above operations using the circuit shown in Figure 2. The frequency response of the circuit shown in Figure 2 is:

$$\frac{V_{OUT}}{V_{IN}} = \frac{R_1 + R_2}{R_1} \frac{1/R_3 C}{j\omega + 1/R_3 C} \quad (1)$$

so the amplitude response of the circuit is:

$$\left| \frac{V_{OUT}}{V_{IN}} \right| = \frac{R_1 + R_2}{R_1} \frac{1/R_3 C}{\sqrt{\omega^2 + 1/R_3 C^2}} \quad (2)$$

The amplitude response of the overall signal conditioning circuit of Figure 2 is shown in Figure 3. The low frequency gain (as $\omega \rightarrow 0$) of the circuit is $\frac{R_1 + R_2}{R_1}$, and the filter's output goes to zero at high frequencies (as $\omega \rightarrow \infty$). The *cutoff frequency* of the circuit indicates at what frequency the filter's output begins to decrease rapidly; for our circuit, the cutoff frequency is $\omega_c = 1/R_3 C$. The DC gain can be used to amplify the output of the piezoelectric sensor in the pass band, while the stop band can be used to eliminate the noise in the signal at high frequencies. (Signals entering the circuit with frequencies below the cutoff frequency – the pass band – are amplified; signals entering the circuit with frequencies above the cutoff frequency – the stop band – are attenuated.)

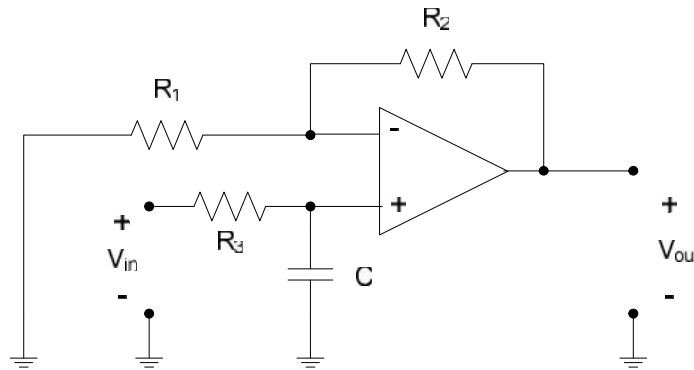


Figure 2. Signal conditioning circuit.

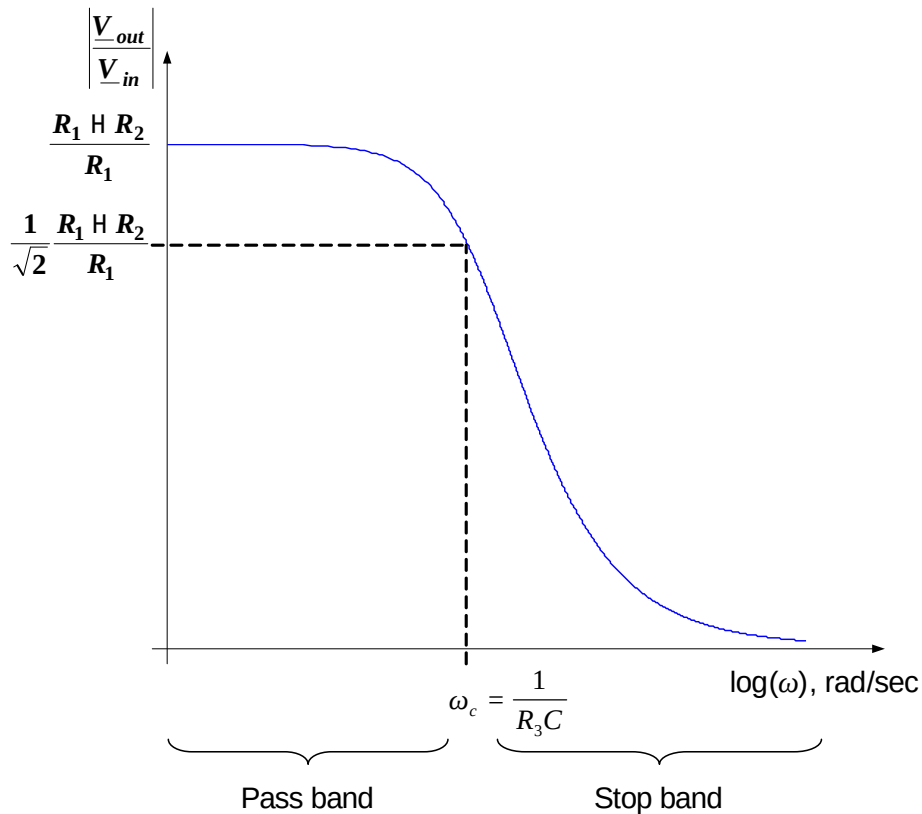


Figure 3. Signal conditioning circuit amplitude response.

Pre-lab:

- ANALYSIS** a. Using equation (1) as your starting point, show that the amplitude response of the circuit of Figure 2 is as provided in equation (2)
- ANALYSIS** b. Using equation (1) as your starting point, determine the phase response of the circuit of Figure (3)
- ANALYSIS** c. Determine the cutoff frequency of the circuit of Figure 2. What is the gain and phase of the circuit at the cutoff frequency?

Lab Procedures:

- ANALYSIS** a. Design a circuit like that shown in Figure 2 (e.g. choose R_1 , R_2 , R_3 and C) to provide a DC gain of approximately two and a cutoff frequency of roughly twice the sensor's dominant vibration frequency as determined in Part I of this lab assignment.
- DATA** b. Construct the circuit you designed in part (a). Record actual resistance and capacitance values.
- DATA** c. Measure the frequency response (amplitude and phase) of your circuit. To do this, use the function generator to apply sinusoidal inputs to the circuit. Record input voltage amplitude, output voltage amplitude, the time difference between the two, and frequency for at least 5 or 6

values of frequency; make sure you use a range of frequencies which includes your cutoff frequency. Note: Appendix B of this lab assignment provides tips relative to gain and phase measurement.

DEMO

- d. Demonstrate operation of your circuit to the TA and have them initial the appropriate page(s) of your lab notebook and the lab worksheet.

ANALYSIS

- e. Calculate the gain and phase of your circuit for the frequencies measured in part (c). Plot the amplitude response in your lab notebook; use a logarithmic scale on the frequency axes of your plots. Discuss your measured response vs. the expected response from your pre-lab calculations. In particular, compare the actual and expected gain and phase at low frequencies, high frequencies, and the cutoff frequency.

3. Overall System Integration:

We will now integrate the signal conditioning circuit designed and built in Part II with the sensor of Part I. Since our signal conditioning circuit's cutoff frequency is approximately twice the natural frequency of the sensor, most of the low frequency components in the sensor's output should lie within the pass band of the signal conditioning circuit. The goal is to amplify the "important" part of the response of the sensor and remove the (hopefully) less significant higher frequency content in the sensor output – high frequency noise, for example, will be removed by the low-pass filter. One possibly important drawback to this approach, of course, is that desirable higher-frequency information will also be removed from the data.

Pre-lab:

None

Lab Procedures:

DATA

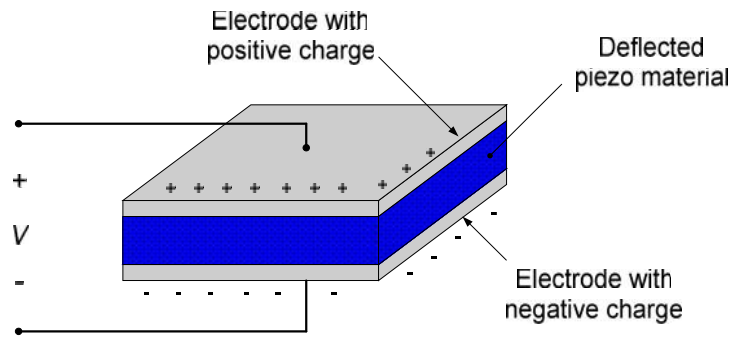
- a. Apply the sensor output voltage to the input terminals of the signal conditioning circuit, $V_{IN}(t)$. Using the oscilloscope, measure both $V_{in}(t)$ from the sensor and the signal conditioning unit's output voltage, $V_{OUT}(t)$ in Figure 2. "Flick" the sensor and record an image of the oscilloscope window, showing the voltages $V_{IN}(t)$ and $V_{OUT}(t)$. Comment on your results relative to your expectations.

DEMO

- b. Demonstrate operation of your circuit to the TA and have them initial the appropriate page(s) of your lab notebook and the lab worksheet.

Appendix A – Piezoelectric sensors

Some materials (certain crystals, for example) produce a charge when they are deflected; this is called a *piezoelectric* effect; materials which exhibit this property are called *piezoelectric materials* or *piezo materials*. If a piezoelectric material is sandwiched between two conductors, or *electrodes*, a voltage difference is produced between the electrodes when the material is deflected. A typical arrangement is shown in the figure below.



A constant (or *static*) deflection of a piezoelectric material will result in a fixed charge at the sensor's electrodes. *Leakage effects*, either within the piezoelectric material or the electronics associated with the sensor, cause this charge to dissipate with time. Thus, piezoelectric sensors cannot generally be used for *static* measurements (measurement of constant values) since the sensor's output voltage will decay to zero if the piezoelectric material's deflection is constant. Piezoelectric devices do, however, make excellent *dynamic* sensors (sensors which record time-varying phenomena) in which the piezoelectric material deflects rapidly relative to the leakage rate.

Piezoelectric sensors are often used in the measurement of time-varying pressures, accelerations, and forces. In these applications, the sensor is set up so that the process to be measured results in deflection of the piezoelectric material; the resulting voltage is used to indicate the desired physical parameter. A force applied to the material, for example, induces a stress in the material with a corresponding deformation of the material.

The piezoelectric sensor provided in the analog parts kit consists of a very thin piezoelectric film sandwiched between two printed electrodes and laminated to a polyester substrate. Contacts are provided to make connections to measure the response voltage. The device is shown below.

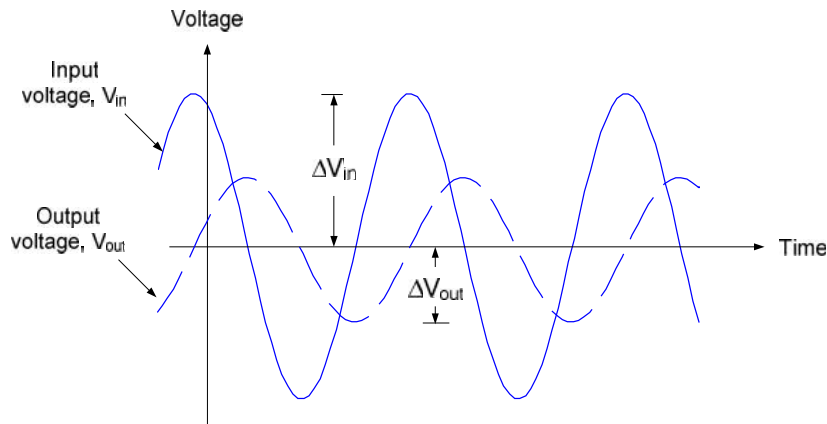


Appendix B – Measuring Gain and Phase:

The gain of a system at a particular frequency is the ratio of the magnitude of the output voltage to the magnitude of the input voltage at that frequency, so that:

$$\text{Gain} = \frac{\Delta V_{out}}{\Delta V_{in}}$$

where ΔV_{out} and ΔV_{in} can be measured from the sinusoidal input and output voltages as shown in the figure below.



The phase of a system at a particular frequency is a measure of the time shift between the output and input voltage at that frequency, so that:

$$\text{Phase} = \frac{\Delta T}{T} \times 360^\circ$$

where ΔT and T can be measured from the sinusoidal input and output voltages as shown in the figure below.

