

ME 360: FUNDAMENTALS OF SIGNAL PROCESSING, INSTRUMENTATION AND CONTROL

Experiment No. 3 – Noise Reduction Techniques, Instrumentation Amplifiers, and Strain Gauge Measurements

1. CREDITS

Originated: N. R. Miller, November 1991
Last Updated: S. S. Igram, September
2020

2. OBJECTIVES

- (a) Introduce the Wheatstone Bridge
- (b) Use a virtual Wheatstone Bridge to find the resistance of an unknown resistor.
- (c) Introduce the use of metal-foil strain gauges and build a simulated half-bridge based on the WB.
- (d) Measure the frequency and decay constant of a vibrating cantilever beam using a pair of strain gauges in a half-bridge configuration, an instrumentation amplifier to amplify the bridge output, and the oscilloscope to observe the resulting voltage waveform.

3. KEY CONCEPTS

- (a) Strain gauges are commonly used to measure strain (strain gauge), force (load cell), and pressure (pressure transducer). Both static and dynamic measurements are possible.
- (b) The resistance of a strain gauge increases slightly under tension and decreases slightly under compression. Gauges are used in pairs to reduce the effect of temperature changes on strain readings.
- (c) Strain-gauge measurements require a bridge circuit because the resistance change is very small.
- (d) Accurate strain-gauge bridge measurements require an amplifier with a high common-mode rejection ratio and a low output offset. Such an amplifier is called an "instrumentation amplifier".
- (e) The dynamic characteristics of mechanical systems can be effectively modeled as lumped spring-mass-dashpot systems.

4. SYNOPSIS OF PROCEDURE

- (a) Build the Wheatstone Bridge using MATLAB/Simscape.
- (b) Determine analog amplifier gains using device data sheets.
- (c) Tune a variable resistor in the WB to balance arm voltages and calculate an unknown resistor value.
- (d) Simulate a strain-gauge-equipped cantilever-beam apparatus.
- (e) Use the strain gauges, instrumentation amplifier board, and oscilloscope to measure the frequency and decay constant of the vibrating cantilever beam.

5. Background

To make strain gauge measurements, we use the bridge circuit shown in Fig. 5.1.

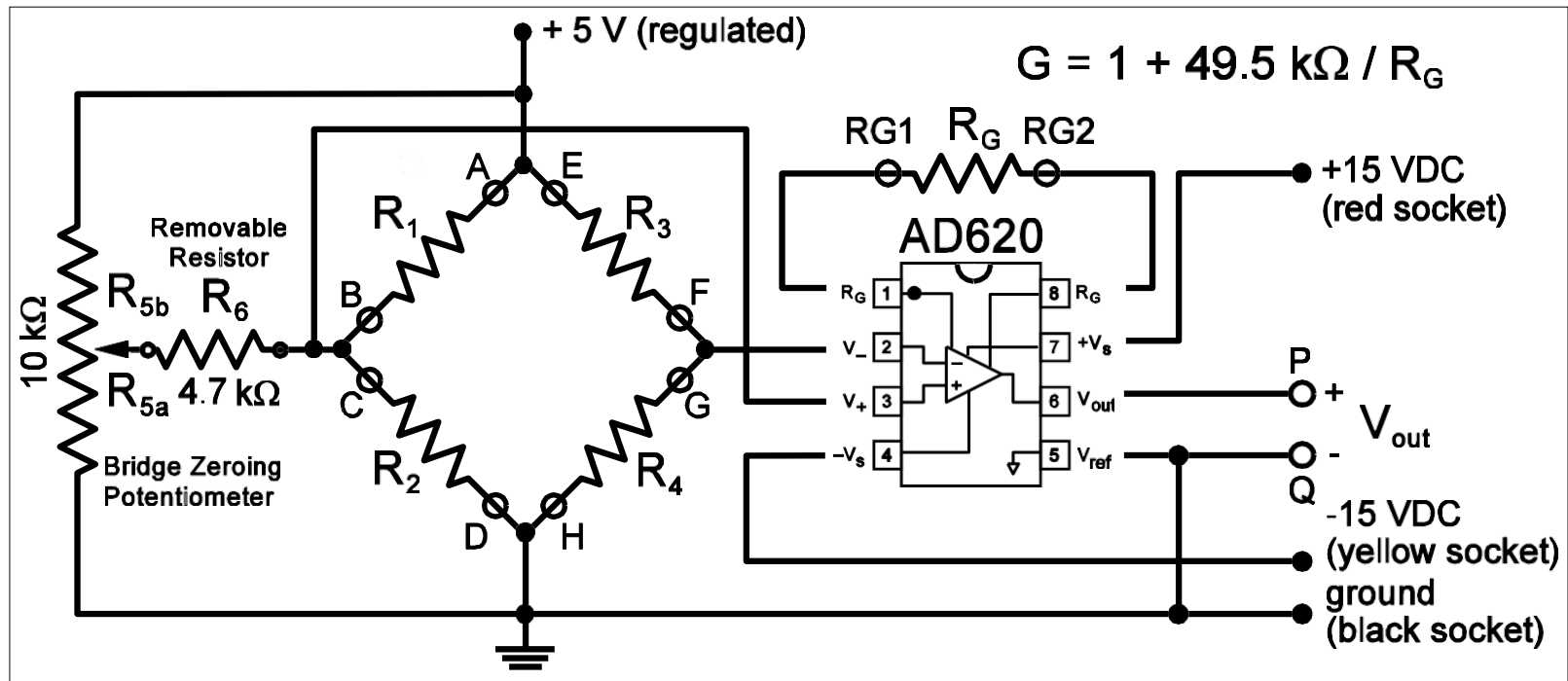
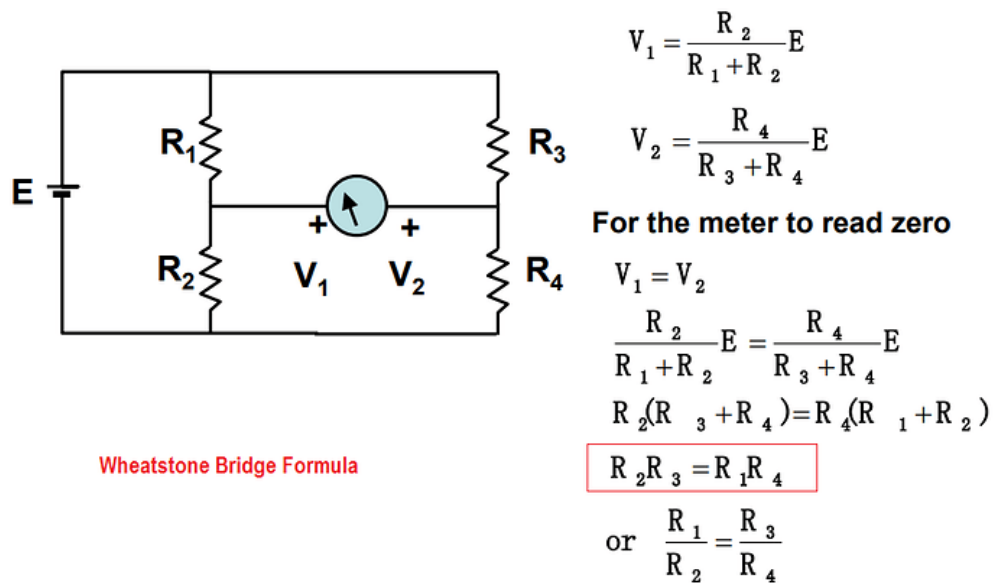


Figure 5.1 AD620 Instrumentation Amplifier Circuit Board Schematic.



This circuit board has three notable features as follows:

- Connections are provided for four external resistors $R_1 - R_4$ that together form a resistance bridge. The bridge excitation voltage is regulated at 5 VDC.
- The circuit includes a 10-k Ω potentiometer that can be used to zero the output at a particular reference condition.
- An Analog Devices AD620AN instrumentation amplifier is used to amplify the bridge output voltage.

The circuit board can be configured as a quarter bridge, a half bridge, or a full bridge depending on how the four resistor positions are populated as given below.

Bridge Type	Gauges	Fixed Resistors	Comment
quarter	R_2	R_1, R_3, R_4	no temperature compensation
half	R_1, R_2	R_3, R_4	good temperature compensation
full	R_1, R_2, R_3, R_4	none	same as half bridge except twice the output

In this experiment, we use a cantilever beam apparatus with two gauges in a half-bridge configuration. One gauge is in tension, and the other is in compression as shown in Fig. 5.2. The potentiometer and additional 4.7-

k Ω resistor are needed because it is impossible to exactly match the gauge and fixed resistors. The voltage reference can thus be adjusted up and down to zero the amplifier output. This method can also potentially correct for a nonzero output offset.

An instrumentation amplifier is a high-performance operational amplifier with a very high common-mode rejection ratio and a very low output offset. We shall first consider what these characteristics mean and then discuss why they are important. We begin by stating the amplifier equation and defining common-mode rejection ratio (CMRR).

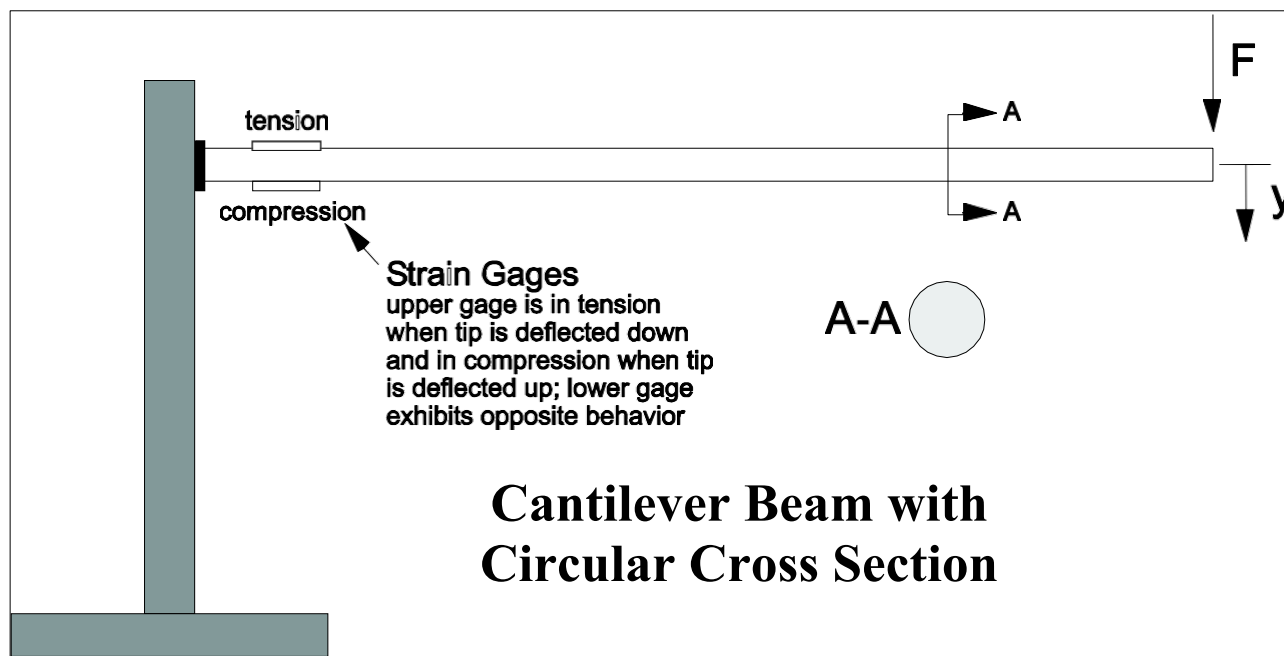


Figure 5.2 Cantilever Beam Apparatus Showing Location of Strain Gauges.

Amplifier Equation

$$V_{\text{out}} = G(V_+ - V_-) + G_{\text{CM}} \frac{V_+ + V_-}{2} + V_{\text{offset}}$$

where G = normal-mode (differential) gain [-], G_{CM} = common-mode gain [-], V_{offset} = amplifier offset [V], V_+ = positive input to amplifier [V], and V_- = negative input to amplifier [V].

Common Mode Rejection Ratio

$$\text{CMRR} = 20 \log_{10} \left(\frac{G}{G_{\text{CM}}} \right)$$

G_{CM} and V_{offset} are both ideally zero ($\text{CMRR} = \infty$) for an ideal operational amplifier. The common-mode gain is not 0 for a real amplifier because manufacturing an integrated circuit amplifier with two identical input stages is impossible. The output offset is not 0 because making a device with a perfect output stage is also impossible. Laser trimming the integrated circuit after the pattern is printed on the chip material can minimize these minor manufacturing defects. This extra step, which is roughly equivalent to machining a part after it is cast, gives the amplifier its high-performance characteristics.

A high common-mode rejection ratio is needed because the differential voltage is typically only a few millivolts ($V_+ - V_-$) whereas the common-mode voltage is very nearly ($V_{\text{in}}/2$) or $(2.5 \text{ V}) \cdot ((V_+ - V_-)/2)$ in this case. If the common-mode gain G_{CM} is only a factor of 1000 lower than the normal-mode gain G (i.e., the $\text{CMRR} = 60 \text{ dB}$), then the first two terms in the amplifier equation will be comparable in magnitude and the advantages of using a bridge circuit are eliminated. An analogy may help understand this fact. Suppose that one is given the job of measuring the diameter of a rigid wire. Suppose further that the only method for doing so is to lay the wire on a table and measure the distance from the edge of the table to each side of the wire using a long ruler. The difference in the two readings is then the measured diameter. The thickness of the wire is analogous to the differential voltage, and the distance from the edge of the table to the center of the wire is analogous to the common-mode voltage. Suppose further that these measurements must be made simultaneously using two separate rulers. The two rulers are analogous to the two amplifier input stages. Any difference between the two scales will produce an error in the diameter

measurement. Moreover, the difference in scales applies to the total length from the edge of the table and not to the diameter of the wire alone. Having a low common-mode gain (high CMRR) is analogous to having two very nearly identical rulers.

The normal-mode (closed-loop) gain of the amplifier is set by external resistor R_G (*gain* resistor, not *gauge* resistor). We shall measure the exact value of the gain resistor and compute the expected normal-mode gain from the following equation characteristic of the AD620 amplifier.

6. PROCEDURE

6.1 Determining Unknown Resistances Using the Wheatstone Bridge

6.1.1 Set Up the Simscape Diagram

- In your Simulink start menu, select Simscape > Electrical > Create Model.
- Open Library Browser to Simscape > Electrical.
- Find and connect the Simscape blocks for your diagram as in Figure 6.1.1.
- Set DC Voltage Source to 5 V. Make sure AC Voltage is set to 0.
- Set the resistance values of the resistors according to the values shown in the diagram for R1-R4. Disable tolerance effects by setting the tolerance application in each resistor to 'None'.
 - Note:** The Simulink environment only allows us to set blocks in a square grid and rotations of 90 degrees, so the orientation of the resistors in Fig 6.1.1 will look different than that of Fig 5.1 but operates the same.

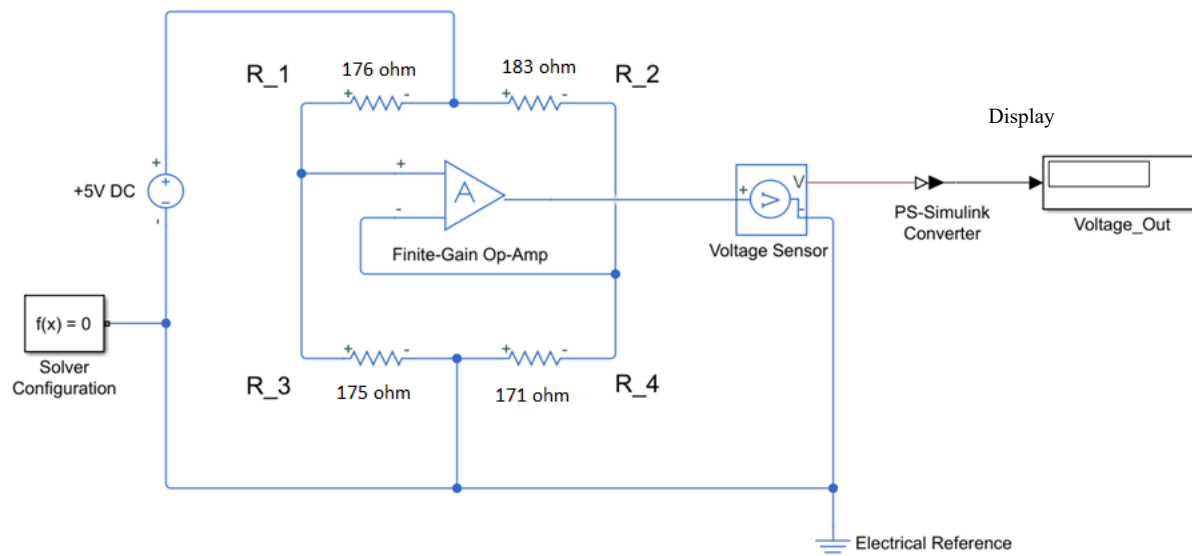


Figure 6.1.1 Simulink/ Simscape diagram for a Wheatstone Bridge with instrumentation op-amp

6.1.2 Determine Amplifier Specifications from Data Sheet

- Using the specification data sheet for the AD620AN instrumentation amplifier (given on the Lab website or available in complete form at www.analog.com), determine the instrumentation amplifier gain, G . Assume that the op-amp in question has a gain resistor value of $R_G = 1 \text{ k}\Omega$.
- Set the gain parameter of the Finite-Gain Op-Amp block to the value of G that was calculated above.
- Run the Simulation and record the voltage difference the display read out.
- Switch the values of R_1 and R_2 so that $R_1 = 183\Omega$ and $R_2 = 176\Omega$. Run the simulation and record the new voltage difference. What did you notice when the resistors were swapped?
- Set R_1 and R_2 back to their original values.

6.1.3 Adding a Resistor of Unknown Value

- Download and extract the R_x .zip file from the lab website. Once extracted, open the R_x .slx model.
- Replace the resistor in position R_4 with the R_x block in your Wheatstone Bridge model.
- Run the simulation and record the voltage value on the display.

6.1.4 Calculating the Unknown Resistance

- Adjust the resistance value of R_3 until the branches/arms of the WB are balanced (Voltage_out \sim 0 Volts).
- Once the bridge is balanced, use the following formula to calculate the unknown resistance, $R_x = \frac{R_2}{R_1} R_3$.
- Record the resistance of R_x you calculated.

6.2 Simulation of a Cantilever Strain-Gauge

6.2.1 Set Up the Simscape Diagram

- In your Wheatstone Bridge model, clicking on the + symbol in the upper left corner to open a new Simulink model - without closing your WB model.
- Copy and paste the WB diagram into the new model by clicking and dragging over the entire diagram to select. Copy the diagram by using Ctrl+C (or any copying method). Paste the diagram by clicking in the empty space of the blank model and using Ctrl+V (or any pasting method).
- Replace resistors at positions R_2 and R_4 with Strain Gauge blocks located in Simscape > Electrical > Sensors & Transducers. Set each Gauge Resistance to 350 ohms and Gauge Factor to 0.015.
- Change R_1 and R_3 to 350 ohms
- Connect Simulink-PS Converters to the remaining ports of the strain gauges.
- Add two more display blocks with numeric format set to long, labeling them as shown in Fig 6.2.1.
- Download and extract the SRG_Display_Calc zip file from the lab website. Copy and paste the SRG_Display_Calc subsystem and Strain - E dashboard slider into the model.
- Connect the SRG_Display_Calc subsystem to the strain gauges and displays as shown in Fig 6.2.1.

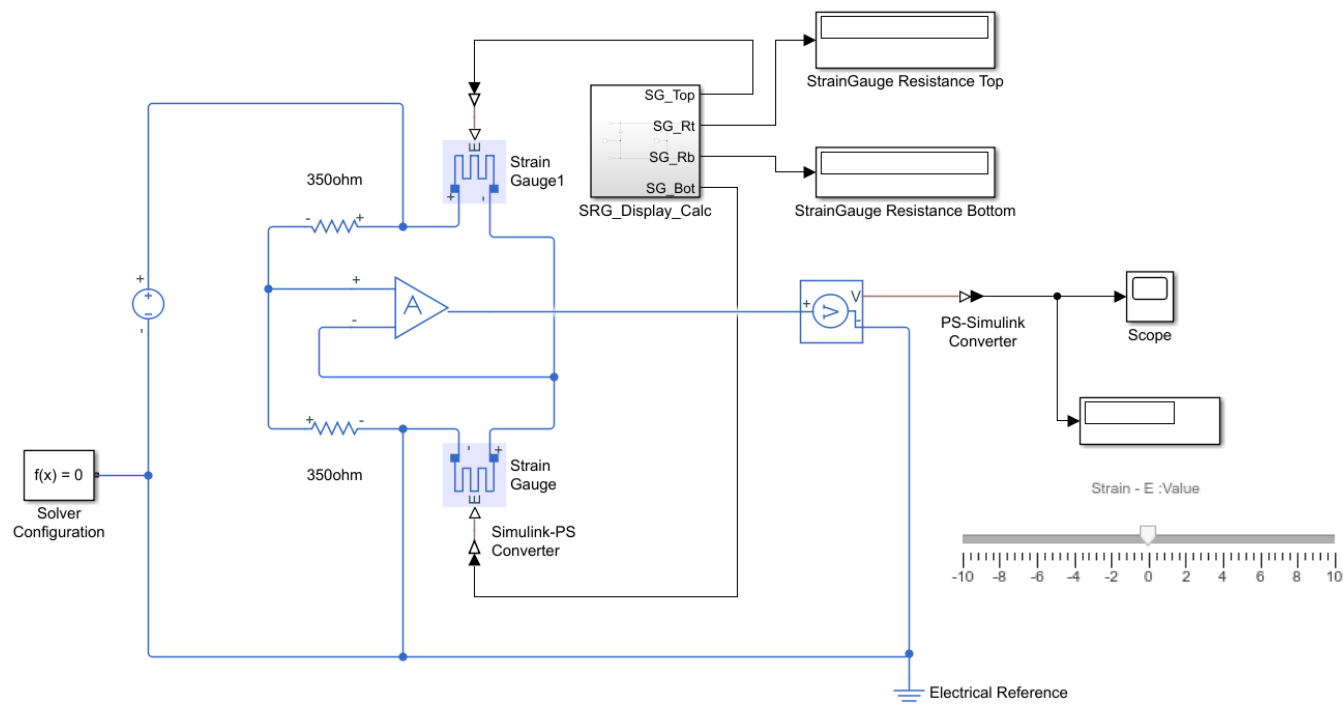


Figure 6.2.1 Simscape diagram for a half-bridge configuration of a Wheatstone Bridge Strain Gauge.

6.2.2 Adjust Model Settings

- (a) To access the model settings, navigate to Modeling (Tab) > Model Settings (Button).
- (b) From the 'Solver' section of the Configuration Parameters window, change the Solver selection Type to 'Fixed-step'. Click the Solver details drop menu and set the Fixed-step size to 0.001 (one millisecond).
- (c) Go to the 'Data Import/Export' section and uncheck the box for "Single simulation output". Close the Configuration Parameters window.
- (d) Change the Stop Time to 'inf' (Matlab's native variable for infinity).
- (e) Open Pacing Options by clicking the down arrow under the Run button. Check the 'Enable pacing...' box and close.

6.2.3 Run Simulation and Observe

- (a) Open the scope and run the simulation. The scope will behave as an oscilloscope, displaying only the most recent window of time.
- (b) Use the Slider by clicking and dragging the strain value ticker as the simulation runs. You will be able to observe the effects of compression and tension on the strain gauges in real time through the scope.
- (c) As you adjust the slider input notice the resistance values in the displays "StrainGauge Resistance Top" and "StrainGauge Resistance Bottom". One gets larger while the other gets smaller. This is what happens to an actual strain gauge pair when one gauge is in tension and the other gauge is in compression. So moving the slider is simulating pressing down or pulling up on a cantilever beam that has one strain gauge on the top side of the beam and one strain gauge on the bottom side of the beam.
- (d) Stop the simulation at any point and save the scope results from your experimentation.

Frequency and Decay Constant of Vibrating Beam

6.2.4 Set Up the Simscape Diagram

- (a) Open the SRG_Display_Calc subsystem by double clicking on the block.
- (b) Disconnect the constant block 'Strain – E' from the diagram by selecting and deleting the connector line. Right click the block and select 'Comment Out'.
- (c) Add the following blocks to our subsystem: Discrete Impulse & Transfer Function.
- (d) For the discrete impulse, set the Delay to 100, Sample time to 0.001, Samples per frame to 1. This will simulate someone "flicking" the physical beam, i.e. applying a momentary force and allowing for free vibrations.
- (e) The lumped parameter transfer function of a cantilever beam is given by

$$TF(s) = \frac{1}{Ms^2 + Ds + K}$$

Where M is the mass of the beam, D is the cross-section diameter, and K is the spring constant of the beam.

- (f) To implement the behavior of the cantilever beam used in the physical lab as a transfer function in Simulink, you will need the beam parameters found in the appendix.
- (g) Set the transfer function numerator to 1,000 (for ease of computation later), and the denominator to [M, D, K], by plugging in the parameters found in step (f).
- (h) Ensure the new blocks are connected to the subsystem before returning to the main model.

6.2.5 Run the Model and Collect Data

- (a) Adjust the stop time to 10 seconds.
- (b) Add the 'To Workspace' block to the model.
- (c) In the 'To Workspace' block name the variable 'V_out'. Change the Save Format to Array and Save 2-D signals as: 2-D Array.
- (d) Run the model and observe. Save and submit the Scope data.

6.2.6 Calculate Damping Ratio, Time Constant, and Natural Frequency Using Logarithmic Decay

- (a) Copy and paste the function code provided for Logarithmic_Decrement into a new MATLAB script file.
- (b) Saving the file will automatically name it with the function handle name and add it to the current library folder.
- (c) Run this function on the data saved from the previous section.
- (d) Save and report the damping and time constants for the vibrating beam and the plot produced.

Logarithmic Decrement Function

```
function [Delta,Zeta_damp,Wn]=Logarithmic_Decrement(tout,V_Out)
%% Import Data
[P_amp,P_t]=findpeaks(V_Out,tout);
n_peaks=length(P_amp);
T = (P_t(n_peaks)-P_t(1))/(n_peaks-1); % Average Period of Peaks
%% Calculate Logarithmic Decrement
Delta_all = zeros(n_peaks,1);
for nn = 1:n_peaks-1 %We go to 'n-1' since the last peak will have no sucesor
    Delta_all(nn)= log(P_amp(nn)/P_amp(nn+1));
end

Delta = mean(Delta_all); %Calculate Average Logarithmic Decrement
Zeta_damp = 1/sqrt(1+((2*pi/(Delta))^2)); %Assesses Damping Constant
Wn = 2*pi/(T*sqrt(1-Zeta_damp^2)); % Calculate Natural Freq
%% Plot Scope and Peak Data
figure
plot(tout,V_Out,'b',P_t,P_amp,'or')

end
```

7. INSTRUCTIONS FOR THE REPORT

7.1 Format

You are expected to write a **brief** report demonstrating your work and your understanding of the concept. The report should have the following:

- Must be in pdf format.
- Name the file as 'Lastname_Firstname_360_Lab3.pdf'.
- Use either 11pt or 12pt font, Arial/Calibri/Times New Roman, single spaced.
- 1" margins.
- Number all of your pages.
- Add a title page.

7.2 Content

Your report should include all of the following:

Noise Demo Data Sheet:

- Include with your report the following tables. Fill out each section with the information present in the demo video on the lab website.
- Include with each table a short description of your observations during the corresponding parts of the demo.

1. EFFECT OF SHIELDING ON ELECTROMAGNETICALLY COUPLED NOISE

	Peak-to-peak Noise Level	
Shield	Normal	Close to AC Power Cord
Ungrounded		
Grounded		

2. EFFECT OF CONDUCTOR TWISTING ON INDUCTIVELY COUPLED NOISE

Loop	Peak-to-peak Noise Level
Untwisted	
Twisted	

Concept Questions:

- 1) What two types of noise are studied in the demo video?
- 2) What type of noise is shielding effective against? What type of noise is twisted-pair cabling effective against?
- 3) What is the purpose of the tape head demagnetizer in the demo video?
- 4) How many gauges are installed on the cantilever beam?
- 5) What bridge configuration (quarter, half, or full) is used in the demo? How many gauges would be used for the remaining configurations?

Simulation Results/ Discussion

- What was the gain calculated for the Finite-Gain Op-Amp block using the AD620 Data Sheet?
- In the Wheatstone Bridge example, submit your Simulink diagram with the voltage display readout for the unknown resistor (this is prior to balancing the branches of the Bridge).
- What was the final resistance used for R_3 that balanced your Wheatstone Bridge? What was the resistance value you calculated for the unknown resistor block?
- Submit your Simulink diagram and scope data from the strain gauge setup experiment (Section 6.2.3).
- Submit a screenshot of your modification to the SRG_Display_Calc subsystem.
- What was the transfer function you found using the beam parameters?
- Submit results from your Logarithmic_Decay code and your plot with labeled axes, title, and legend.

APPENDIX A. NOISE AND INTERFERENCE

Noise refers to any unwanted signal superimposed on the signal of interest. In normal usage, the word "signal" by itself means only the desired signal, and the word "noise" means the unwanted signal. The signal-to-noise ratio is then simply the ratio of the two levels typically measured in terms of root-mean-square values. A high signal-to-noise ratio is very desirable.

Noise may come from the external environment in which case we call it "interference" or "electromagnetic interference" (abbreviated "EMI"). Because interference is almost always the dominant component of noise for the applications of interest to us, we treat "noise" and "interference" as more or less synonymous. We should note, however, that noise can also arise from internal sources in which case it is "intrinsic noise". Sources of intrinsic noise include:

- (a) temperature changes or gradients in the system (thermal noise),
- (b) random changes in molecular states,
- (c) the contact of two or more dissimilar metals (galvanic noise),
- (d) the action of an electrolyte in the presence of two or more dissimilar metals,
- (e) the flexing of electrical conductors (triboelectric noise), and
- (f) conductor motion in a static magnetic or electric field.

Focusing on external noise or interference, we can logically envision a source-receptor arrangement where noise created at a remote source is transmitted by electromagnetic radiation to the receptor. The receptor in this case consists of our instrumentation and all of its associated wiring. Most interference is actually a composite of many sources, but focusing on a single source-receptor combination is satisfactory for illustrative purposes. In the previous experiment, we considered filtering as a method of combating noise contamination once it becomes part of the signal. In this experiment, we shall focus on reducing the amount of externally generated noise that becomes part of the signal in the first place. Methods for reducing noise contamination include (a) reducing the strength of the noise source, (b) increasing the distance between the source and the receptor, (c) blocking the noise (shielding), and (d) reconfiguring the wiring to reduce noise reception.

Reducing the strength of the noise source is typically not an option for us. Federal Communications Commission regulations place limits on the noise that different types of equipment can produce. As users, very little can be done beyond ensuring that the equipment is properly maintained so as to meet those standards. Moreover, the regulations may not apply to the large-scale industrial equipment that is often the primary noise source, nor do FCC regulations help much with AC line noise or with noise from radio frequency transmitters such as emanate from radio stations and cellular telephones. We are literally awash in RF interference owing to the heavy use of RF transmission in the communications industry.

Increasing the distance from the noise source may be an option if the noise source is close by. This approach is most effective when the receptor is in the near field of the source as is more fully explained below. If the source is already quite remote, then reasonable increases in distance will generally have a small effect.

Reconfiguring the wiring can be quite effective against certain types of noise, but this approach is more or less a black art often involving significant trial and error. In this experiment, we shall limit ourselves to one very important example of this approach; namely, twisting the signal and return lines to reduce inductively coupled noise. We shall examine this latter approach in more detail shortly.

Shielding is generally one of the best methods at our disposal for reducing interference. However, the effectiveness of shielding depends on many factors. Understanding these factors enables us to better select and use shielding to deal with often frustrating noise issues.

A.1 Shielding Effectiveness

Type of Noise Source

A proper determination of shielding effectiveness involves the very difficult task of solving Maxwell's Equations for the propagation of electromagnetic waves. Much can be learned, however, from simple analytical solutions for two ideal source types: (a) an electric dipole (for example, two equal positive and negative charges separated by a small distance) and (b) a magnetic dipole (for example, a single loop of wire with a current flowing through it). Even these simplified solutions involve a host of other assumptions, but, fortunately, these assumptions are at least approximately valid and thus do not affect the trends and major conclusions that can be drawn from the analysis. The difference between the two source types centers on the relative magnitude of the electric and magnetic fields

produced. A magnetic dipole is the limiting case for high-current devices such as motors, transformers, and electromagnets that produce a much greater magnetic field. An electric dipole is the limiting case for low-current devices that produce a much greater electric field. As a rough rule of thumb, the magnetic field is "greater" if the load impedance is less than 377Ω . Conversely, the electric field will be "greater" if the load impedance is more than 377Ω . To see what this means in terms of everyday experience, a 120-VAC device that draws more than 19 W will have a greater magnetic field. (Use the equations $AC \text{ power} = I_{RMS} \cdot V_{RMS}$, $V_{RMS} = I_{RMS} \cdot R$ and $AC \text{ power} = (V_{RMS} \cdot V_{RMS})/R$ to calculate the 19W threshold). Thus, the cable connecting a 200-W computer to the wall socket is a potential source of *inductively* coupled noise. The ratio of the electric and magnetic fields varies with distance from the source approaching a constant value at large distances. If the transmission medium is vacuum or air, the constant value is 377Ω .

Frequency of Noise Source

A second distinguishing characteristic of noise is its frequency. The electromagnetic spectrum is divided into a number of frequency bands with labels such as Very High Frequency (VHF), Ultra High Frequency (UHF), etc. These bands are more numerous and complex than we need here, so we shall simply divide source frequencies into three broad categories with specific examples in each category as follows.

Frequency Range	Examples	Frequencies
low	AC powered equipment	power-line frequency and its harmonics (60 Hz in the US; 50 Hz many countries)
mid	switching power supplies digital electronics	100 – 300 kHz typical 1 – 400 MHz
high	radio transmitters	AM 1000: 1000 kHz; FM 100: 100 MHz UHF radio: 400 MHz; cellular telephone 928 MHz and Higher

Distance from Source

Shielding effectiveness depends on the relative magnitude of the electric and magnetic fields when the transmitted electromagnetic energy reaches the receptor. Because this ratio varies with distance from the source, shielding effectiveness also varies with distance from the source. Two zones are typically identified. The region defined by $r \leq \lambda$ where r is distance from the source and λ is the wavelength of the electromagnetic radiation is known as the near field. The region defined by $r > \lambda$ is then the far field. In the near field, either the magnetic or electric field will dominate depending on which is greater at the source. In the far field, the electric and magnetic fields are approximately in balance, neither dominates, therefore this type of noise is called electromagnetic coupling. This leads to the following classification of source-receptor coupling.

Conditions	Coupling Classification
near field ($r \leq \lambda$); electric field dominates	electric or capacitive coupling
near field ($r \leq \lambda$); magnetic field dominates	magnetic or inductive coupling
far field ($r > \lambda$)	electromagnetic coupling

The dividing line between the near and far fields is given by $\lambda = c / (2 \pi f)$ where $c = 2.99 \times 10^8$ m/s is the speed of light. The dependence on frequency is given below.

Frequency	Example	λ	Frequency	Example	λ
60 Hz	AC power line	800 km	150 kHz	switching	320 m
1 MHz	AM 1000	50 m	100 MHz	FM 100	0.5 m

400 MHz	UHF radio	0.1 m	928 MHz	cellular telephone	0.05 m
---------	-----------	-------	---------	--------------------	--------

The general conclusion that can be drawn from the above information is that one is generally in the near field for AC powered equipment, switching power supplies, and digital electronics and in the far field for most radio frequency sources.

Shielding Material and Thickness

Shielding materials are characterized by their electrical resistivity and magnetic permeability, the later typically given in terms of relative permeability or the ratio of the permeability to that of a vacuum. The permeability of a vacuum is exactly $4\pi \times 10^{-7}$ owing to the way SI units are defined. The characteristics of five common shielding materials are given below.

Material	Resistivity [Ω -m]	Relative Permeability [-]
copper	1.7×10^{-6}	1
aluminum	2.7×10^{-6}	1
steel	10×10^{-6}	1000
stainless steel	72×10^{-6}	500
mu-metal	40×10^{-6}	20000

Shielding effectiveness can be measured in terms of the attenuation of the noise signal expressed in dB. The following two tables show how effectiveness varies for electric and magnetic dipole sources, respectively.

Electric Dipole (Capacitive 1 st 4 items, Electromagnetic 2 nd 4 items)			Shield Effectiveness [dB]				
f	Distance from the source	shield thickness	copper	aluminum	steel	stainless	mu-metal
60 Hz	1 m	0.1 mm	196	192	180	163	168
60 Hz	1 m	1 mm	216	212	201	183	189
60 Hz	1 m	10 mm	236	232	224	204	222
150 kHz	1 m	0.1 mm	128	124	113	95	104
1 MHz	1 km	0.1 mm	78	74	68	46	70
100 MHz	1 km	0.1 mm	81	76	203	71	399
400 MHz	1 km	0.1 mm	89	81	370	110	442
928 MHz	1 km	0.1 mm	99	89	456	155	439

Magnetic Dipole (Inductive)			Shield Effectiveness [dB]				
f	Distance from the source	shield thickness	copper	aluminum	steel	stainless	mu-metal
60 Hz	1 m	0.1 mm	0	0	0	0	5
60 Hz	1 m	1 mm	1	1	3	1	18
60 Hz	1 m	10 mm	6	4	18	9	51
150 kHz	1 m	0.1 mm	28	24	16	4	15

The conclusion to be drawn from the above results is that shielding is very effective against capacitively and electromagnetically coupled noise but not effective against inductively coupled noise especially at the low frequencies typical of most AC-powered equipment. Shielding effectiveness can be increased under these conditions by using high-permeability materials although the effectiveness is still marginal.

To be effective, a shield must be grounded to drain off the noise signal. As a general rule, the shield should be grounded at one end only. This avoids difference in ground levels across long leads (called “ground loops”).

Two types of shielding are in common use. The less expensive, more flexible, but also less effective is metallized plastic film. The second is braided-wire shielding. A high-quality instrumentation cable may have several twisted pairs of conductors each individually shielded with plastic film inside an overall braided-wire shield for the whole cable.

A.2 Using Twisted Pairs to Reduce Inductively Coupled Interference

Given the relatively poor performance of shielding for inductively coupled noise, one is forced to seek some other method for combating noise from motors, transformers, AC power lines, and electromagnets. The best way to reduce inductively coupled interference in cables is to twist the signal and ground wires together in pairs as shown in Fig. A.1 below. Here, we see that by converting the one large loop to many smaller loops, an inherent canceling effect is created that reduces magnetic interference significantly. To minimize magnetically coupled interference, we must make the loops and projected area of the cable in the magnetic field as small as possible. Of course, the first course of action should always be to move the cable as far as possible from the fringe fields of the source.

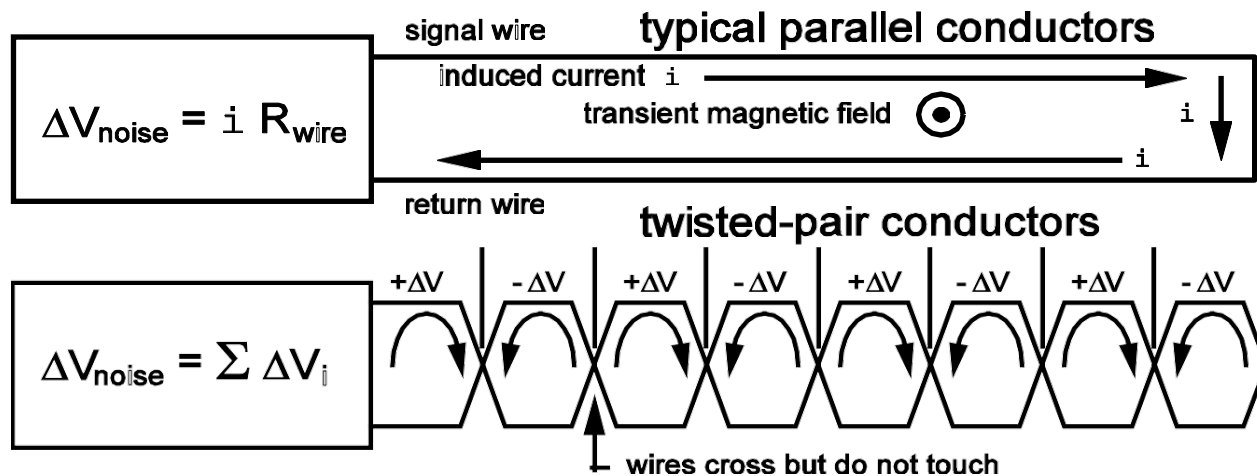


Figure A.1 Magnetically-coupled Interference in Parallel-conductor and Twisted-pair Cabling.

APPENDIX B. BEAM VIBRATION

In this experiment, we shall also study the vibration characteristics of a cantilever beam. Two strain gauges are attached to the beam so that one is in tension and one is compression as shown in Figure 2 below. A half bridge with an amplifier is then used to observe strain as a function of time as the beam vibrates. The analysis of this case is summarized in Tables B.1, B.2 and B.3. These results reveal that the beam will show damped oscillations. We shall measure the frequency and decay rate of these oscillations and compare our results with the values calculated from basic beam parameters.

Table B.1 Summary of Lumped-parameter Vibration Analysis.

Governing Equation	$F(t) = M \frac{d^2 y}{dt^2} + D \frac{dy}{dt} + K y(t)$
Parametric Form of Governing Equation	$f(t) = \frac{d^2 y}{dt^2} + 2\zeta \omega_n \frac{dy}{dt} + \omega_n^2 y(t) \quad \quad \omega_n = \sqrt{K/M}, \quad \zeta = \frac{D}{2M\omega_n}$
Damped Oscillations	$y(t) = \frac{y_0 e^{-\zeta \omega_n t} \sin(\omega_d t + \phi)}{\beta} \quad \quad \beta = \sqrt{1 - \zeta^2}, \quad \omega_d = \beta \omega_n, \quad \phi = \cos^{-1}(\zeta)$

Table B.2 Typical Beam Parameters.

Parameter	Symbol and Definition	Value
Beam Length (mid-support to free end)	L	0.350 m
Beam Diameter	D	0.0127 m
Beam Material	–	Aluminum
Beam Modulus of Elasticity (aluminum)	E	$6.9 \times 10^{10} \text{ N / m}^2$
Beam Density (aluminum)	ρ	2700 kg / m^3
Moment of Inertia of Beam Cross Sectional Area	$I = \pi D^4 / 64$	$1.277 \times 10^{-9} \text{ m}^4$
Actual Beam Mass	$m = \rho \pi D^2 L / 4$	0.120 kg
Spring Constant of Beam	$K = 3 \frac{E}{L^3}$	6165 N / m
Effective Beam Mass	$M = 0.2427 \times m$	0.029 kg

**APPENDIX C. SELECTED DATA SHEETS FOR ANALOG DEVICES AD620 LOW-COST,
LOW-POWER INSTRUMENTATION AMPLIFIER**

The first three pages of the manufacturer's data sheet is at the class web site http://coecsl.ece.uiuc.edu/me360/AD620_pages_1_through_3.pdf. The complete data sheet and much additional information can be downloaded from the manufacturer's web site at [www. analog.com](http://www.analog.com).