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ME 360: FUNDAMENTALS OF SIGNAL PROCESSING, INSTRUMENTATION AND CONTROL

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

1. CREDITS

Originated: N. R. Miller, November 1991
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2. OBJECTIVES

(a) Demonstrate the effectiveness of shielding in reducing electromagnetically coupled noise.
(b) Demonstrate the effectiveness of twisted-pair cabling in reducing inductively coupled noise.
(c) Introduce the use of an instrumentation amplifier for amplifying low-level differential signals with high common-mode voltages.
(d) Introduce the use of metal-foil strain gages.
(e) Measure the frequency and decay constant of a vibrating cantilever beam using a pair of strain gages 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) Noise is the unwanted portion of a signal.
(b) Noise is a common and often serious instrumentation issue.
(c) Noise increases measurement uncertainty and may reduce accuracy below acceptable levels.
(d) Noise reduction is somewhat of a black art drawing heavily on experience and trial and error.
(e) This experiment focuses on two important types of noise: electromagnetically coupled and inductively coupled.
(f) Although the universe of noise types is much larger than just those considered here, important guiding principals are introduced that are helpful in reducing noise problems.
(g) Both types of noise generally come from external sources over which one has no control.
(h) Electromagnetically coupled noise comes primarily from radio frequency sources at 300 kHz and above.
(i) Inductively coupled noise comes from high-current AC wiring, near-by switching power supplies, and electric motors, all of which are common in industry.
(j) Shielding is effective in reducing electromagnetically coupled noise.
(k) Twisted-pair cabling is effective in reducing magnetically coupled noise.
(l) Strain gages are commonly used to measure strain (strain gage), force (load cell), and pressure (pressure transducer). Both static and dynamic measurements are made.
(m) The resistance of a strain gage increases slightly under tension and decreases slightly under compression. Gages are used in pairs to reduce the effect of temperature changes on strain readings.
(n) Strain-gage measurements require a bridge circuit because the resistance change is very small.
(o) Accurate strain-gage 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".
(p) The dynamic characteristics of mechanical systems can be effectively modeled as lumped spring-mass-dashpot systems.

4. SYNOPSIS OF PROCEDURE

(a) Determine the level of electromagnetically coupled noise using a long lead attached to oscilloscope Channel 1. Investigate shielding effectiveness in reducing electromagnetically coupled noise.
(b) Determine the level of inductively coupled noise in a loop formed between the signal and ground connections of oscilloscope Channel 1. Investigate the effectiveness of twisting the signal and ground wires together in reducing inductively coupled noise.
(c) Measure the normal and common-mode gain of the instrumentation amplifier board used for strain gage measurements.
(d) Become familiar with the strain-gage-equipped cantilever-beam apparatus.
(e) Use the strain gages, instrumentation amplifier board, and oscilloscope to measure the frequency and decay constant of the vibrating cantilever beam.

5. PROCEDURE

The procedure is presented at three levels of detail. The lowest level of detail is set forth in the synopsis above and the headings of this section. Review this information first to get a good intuitive feel for the overall scope of the experiment. The second level of detail is a brief description of each specific task often accompanied by a schematic or sketch. This description together with the Data Sheet is usually sufficient to understand and carry out the procedure during the laboratory session. This material should be thoroughly reviewed before coming to the laboratory. Skip over the detailed procedure in preparing for the laboratory session as this information only makes sense when the equipment is at hand.

Important General Information – Please Read Carefully

(a) ***Always turn off the power supplies when changing connections. Dangling leads can easily contact the metal tabletop creating a short, blowing a fuse, creating an unsafe situation or damaging the equipment.***

(b) Disconnect the leads from the instruments when not in use. Connect the instruments last after the wiring is carefully checked.

(c) If your station is missing something, ask your Laboratory Assistant to replace it. Do not take items from other stations.

5.1 Effect of Shielding on Electromagnetically Coupled Noise (TA Demonstration)

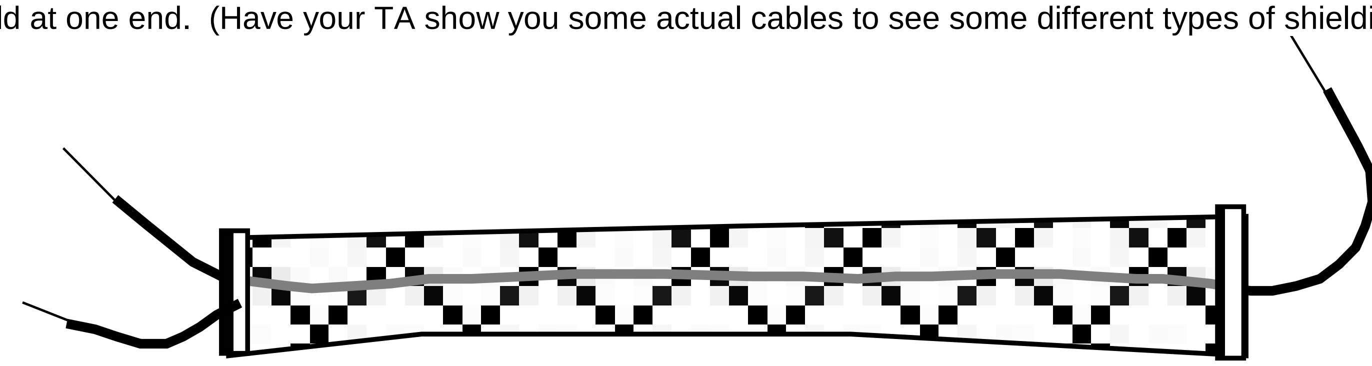
This section will be demonstrated by your lab TA. You will need to record the measurements taken.

5.1.1 Power on Equipment and Locate Lead with Braided Shield

(a) Turn on the power to your station.

(b) Power on the oscilloscope, function generator and digital multimeter. Make sure power to the patch panel is off.

(c) In the drawer of your station find the wire with a braided shield around it. Note the lead attached to the shield at one end. (Have your TA show you some actual cables to see some different types of shielding.)

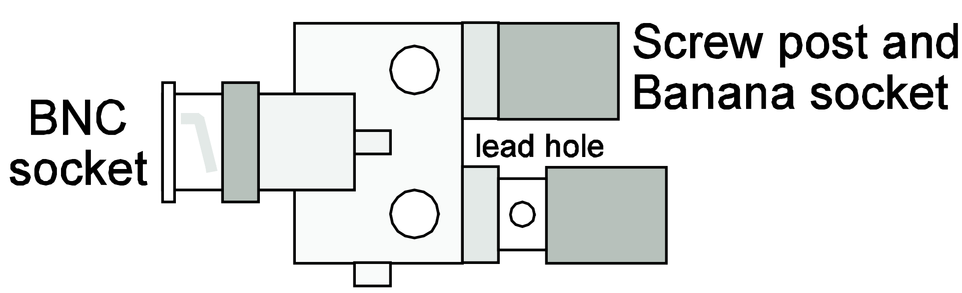


5.1.2 Attach Center Lead to Positive Input of Oscilloscope Channel 1

(d) Attach the center lead with the braided shield to the positive input of oscilloscope Channel 1.

Detailed Procedure for Attaching Shielded Lead

In the drawer of your station, locate the BNC-to-banana-plug adapter. The adapter has a BNC socket on one side and a pair of banana sockets on the other side. Note that the plastic socket covers of the adapter can be screwed out to expose a small lead hole in the side of a metal post. A wire can be inserted into this hole, and the socket cover tightened down to make a connection.



Install the adapter on Channel 1 of the oscilloscope. Attach the center lead (the wire running through the shield) to the red post of the adapter at the same end as the lead attached to the shield. Later, we shall ground the shield to demonstrate the effect of shielding.

5.1.3 Measure Noise Levels With and Without Shield Grounded and Close To and Far From AC Power Cord

(e) Adjust the oscilloscope to display the noise signal present on the wire. Estimate the noise level, and record this level on the Data Sheet. Because the noise signal is random with large fluctuations in peak value, some judgment is required here. The exact method used is not important because we are only interested in relative magnitudes between noise levels measured with and without the shield grounded.

(f) Locate an AC power cable running to your station. Hold the lead with the ungrounded shield next to the power cable. Record this noise level on the Data Sheet. Note any qualitative differences in the noise signal.

(g) Ground the shield and repeat the measurements.

Detailed Procedure for Grounding Shield and Measuring Noise Levels

Connect the lead from the braided shield to the black post of the BNC-to-banana adapter. Record the noise level on the Data Sheet. Hold the lead next to the power cable, and record this noise level on the Data Sheet.

(h) Disassemble the setup, and put the components away. Leave the BNC-to-banana adapter on Channel 1 of the oscilloscope.

5.2 Effect of Conductor Twisting on Inductively Coupled Noise (TA Demonstration)

This section will be demonstrated by your lab TA. You will need to record the measurements taken.

5.2.1 Use Banana Patch Cord to Form Loop on Oscilloscope Channel 1; Apply Inductively Coupled Noise with Tape Head Demagnetizer

(a) Form a loop on oscilloscope Channel 1 with a banana-plug patch cable.

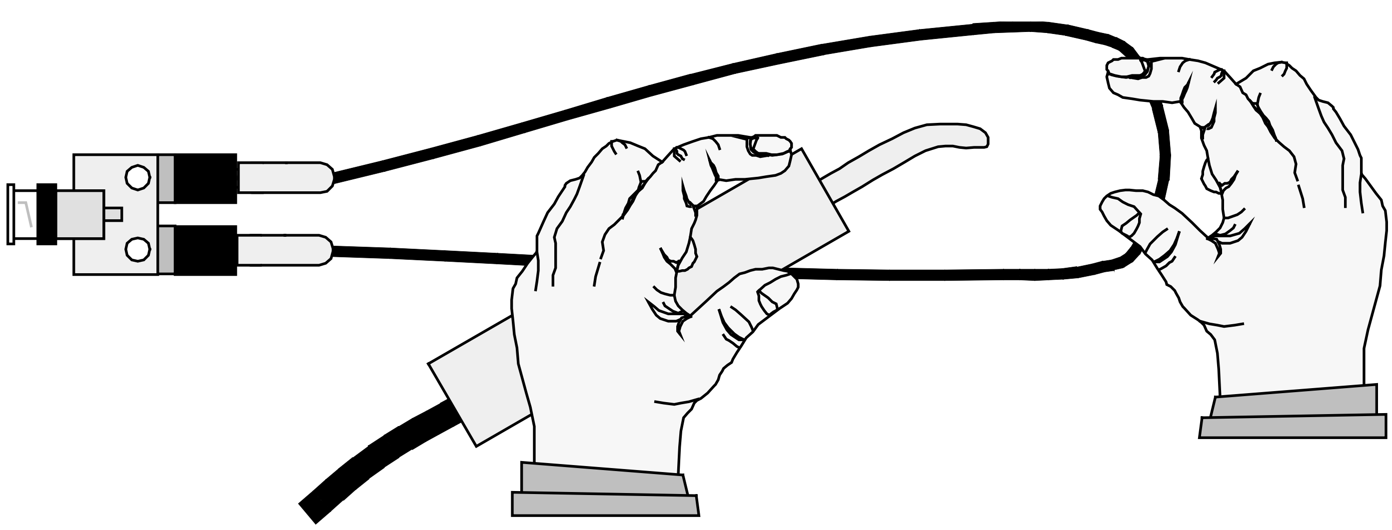
Detailed Procedure for Forming Loop

From the rack of leads, select the longest banana-plug patch cord. Plug one end into the black socket of the BNC-to-banana adapter on Channel 1 of the oscilloscope and the other end into the red socket.

(b) Use the tape head demagnetizer to apply a strong source of inductively coupled noise to the large loop.

Detailed Procedure for Applying Strong Source of Inductively Coupled Noise to Large Loop

Locate the tape head demagnetizer (a moderately strong electromagnet). Plug the demagnetizer into the AC power strip on the bench top. Pull the banana plug patch cord taut at its midpoint so that a loop is formed as shown below. Hold the tip of the demagnetizer inside the loop and turn on the demagnetizer.

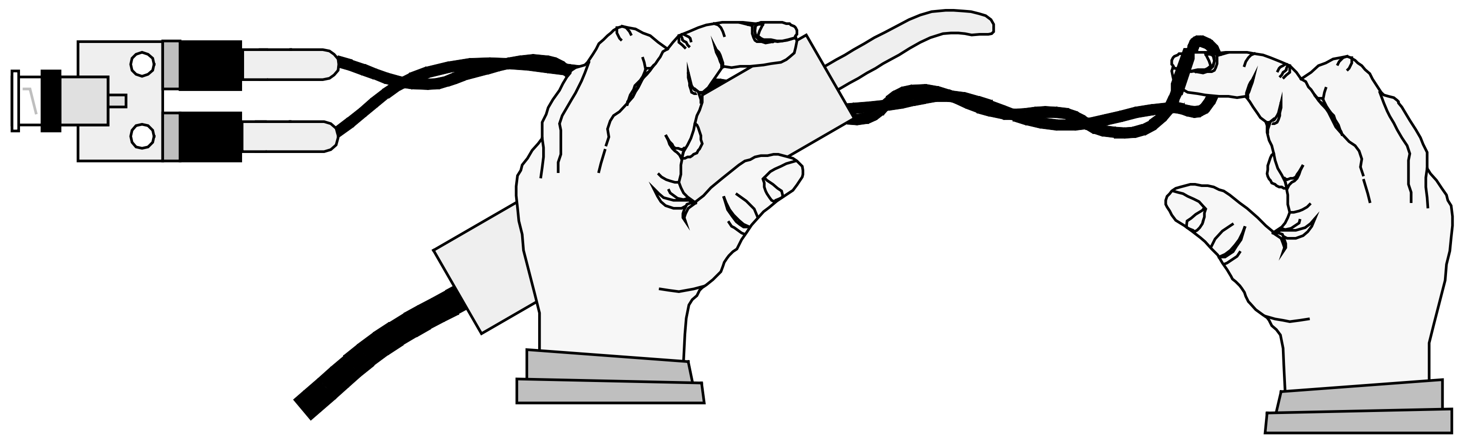


(c) Adjust the controls of the oscilloscope to display the noise signal. Measure the noise level, and record this value on the Data Sheet. Turn the demagnetizer off as soon as a good reading is obtained.

(d) Tightly twist the loop and note the effect on the inductively coupled noise. Record this noise level on the Data Sheet.

Detailed Procedure for Applying Strong Source of Inductively Coupled Noise to Twisted Loop

Tightly twist the banana plug patch cord at its midpoint as shown below. Apply the demagnetizer noise source.



(e) On the Data Sheet, comment on the effectiveness of twisting the signal and return lines in reducing inductively coupled noise.

5.3 Normal-mode and Common-mode Gain of Instrumentation Amplifier

Background and Overview of Procedure

To make strain gage measurements, we use the bridge circuit shown in Fig. 5.3.1.

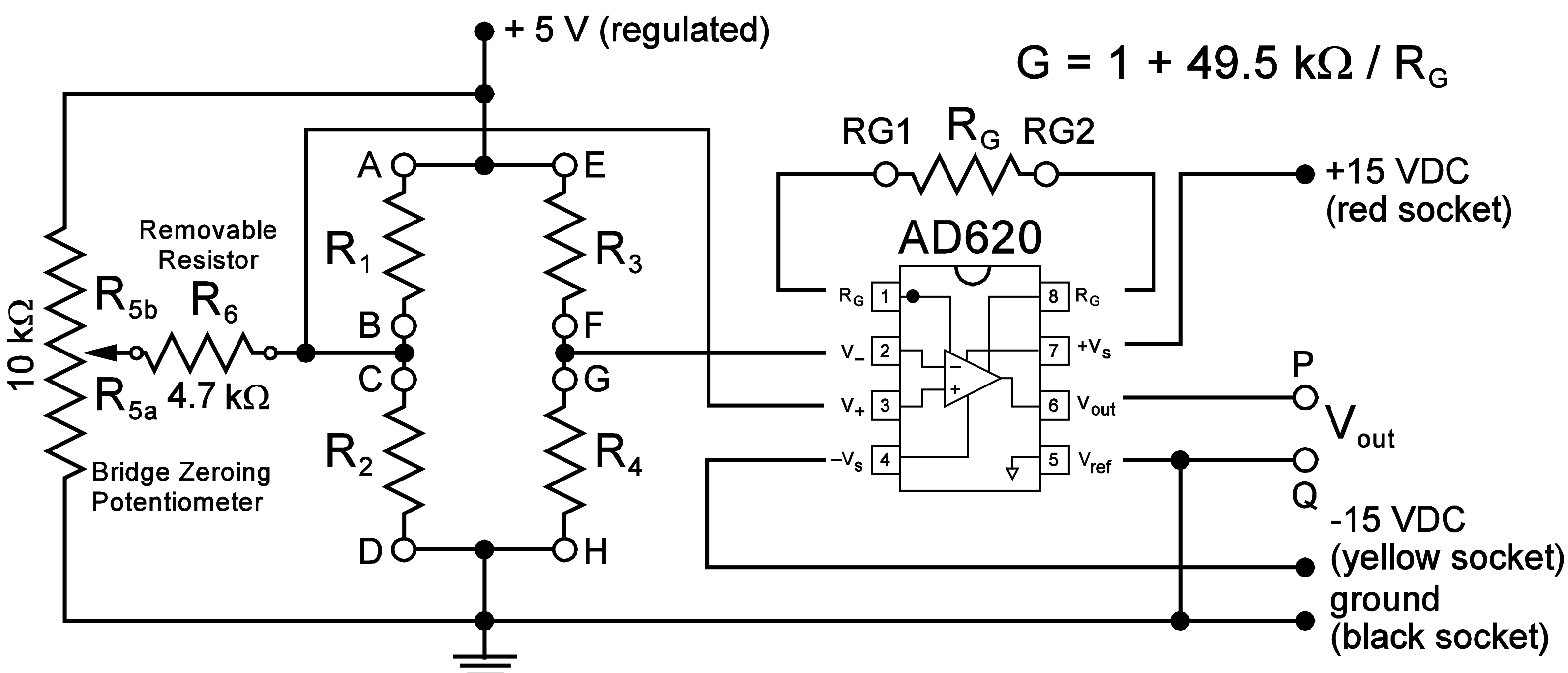


Figure 5.3.1 AD620 Instrumentation Amplifier Circuit Board Schematic.

This circuit board has three notable features as follows:

(a) 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.

(b) The circuit includes a 10-kΩ potentiometer that can be used to zero the output at a particular reference condition.

(c) 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	Gages	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 gages in a half-bridge configuration. One gage is in tension, and the other is in compression as shown in Fig. 5.3.2.

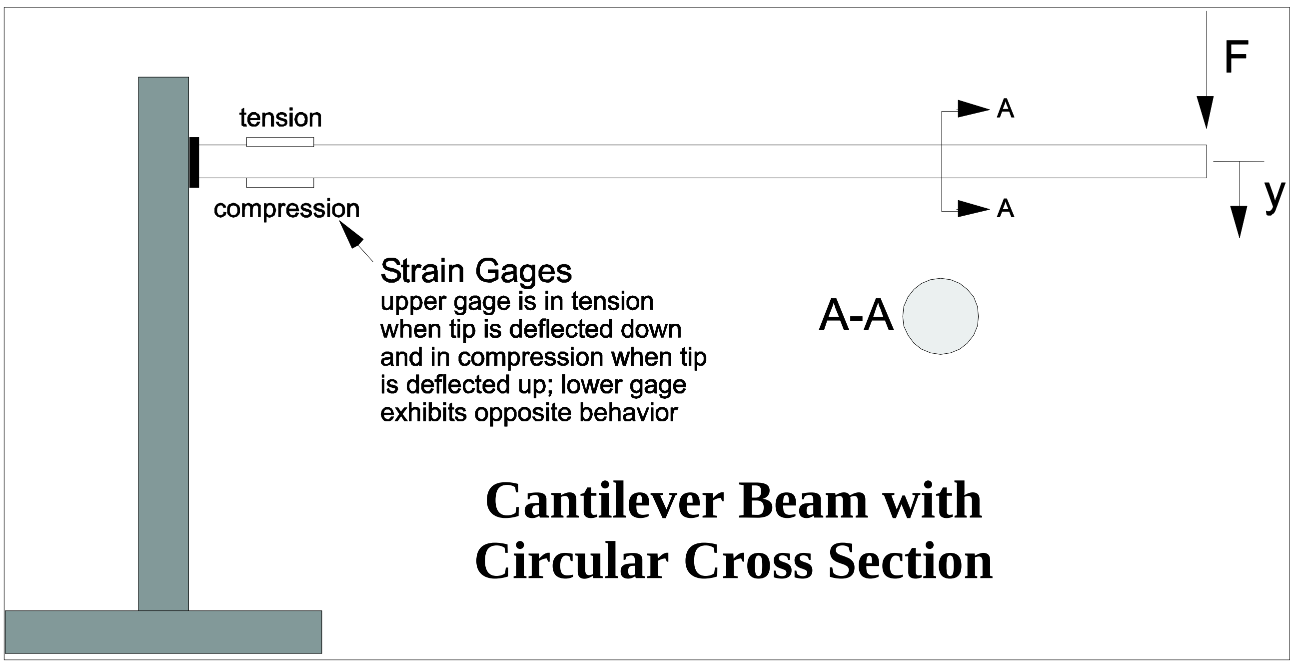


Figure 5.3.2 Cantilever Beam Apparatus Showing Location of Strain Gages.

The potentiometer and additional 4.7-kΩ resistor are needed because it is impossible to exactly match the gage 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).

Amplifier Equation

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

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

$$CMRR = 20 \log_{10} (G / G_{CM})$$

G_{CM} and V_{offset} are both ideally zero (CMRR = ∞) 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_{in} / 2 or 2.5 V (($V_+ - V_-$)/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 CMRR = 60 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 *gage* resistor). The resistance of R_G is nominally 1 kΩ, and the gain is roughly 50. 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.

$$G_{calc} = 1 + \frac{49.4\ \text{k}\Omega}{R_G}$$

In this experiment, we shall also measure the three parameters (G, G_{CM}, and V_{offset}) in the amplifier equation. We shall first measure the output offset V_{offset} by grounding both inputs to the amplifier ($V_+ = V_- = 0$ V). Both the differential voltage ($V_+ - V_-$) and the common-mode voltage ($V_+ + V_-$) / 2 are 0 V, and the measured output voltage is just the output offset. We shall then set both inputs to 5 VDC. The differential voltage remains 0 V, and the common-mode voltage becomes 5 V. Because we know the output offset, we can determine the common-mode gain. Finally, we use the function generator to input a 30-Hz sinusoid with an amplitude of 100 mVp-p and a zero offset. The differential voltage is thus 100 mVp-p and the common-mode voltage is 0 V. By comparing the input and output RMS amplitudes, we determine the normal-mode gain.

5.3.1 Configure Amplifier Circuit Board

Your TA will demonstrate an attempt at measuring V_{offset} and Common Mode Gain. As you will see this is a difficult measurement to make with the noise levels in our lab.

(a) Locate the Analog Devices AD620 Instrumentation Amplifier circuit board shown in Fig. 5.3.3. Identify the various sockets on the board and familiarize yourself with the overall circuit, which is a basic four-resistor bridge with an excitation voltage of 5 V. All four bridge resistors are external to the circuit board; connections are made using the eight banana sockets labeled A through H. (These labels are not on the circuit board.) The voltage divider consisting of R_1 and R_2 is modified so that the bridge output can be zeroed using the potentiometer. The (closed-loop) gain of the amplifier is set using a single plug-in resistor R_G connected between sockets RG1 and RG2.

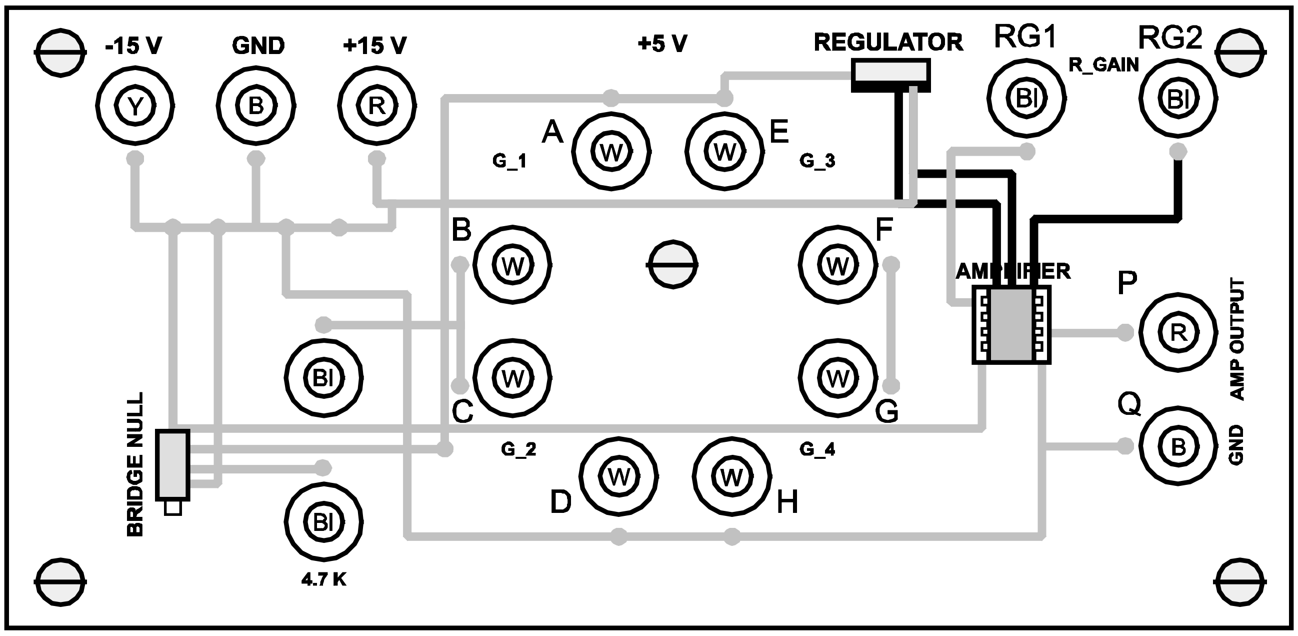


Figure 5.3.3 AD620 Instrumentation Amplifier Circuit Board Layout.

(b) The power leads to the ±15 VDC power supply, located on the left-hand side of the bench top next to the AC power strip, should already be connected. If they are not ask your TA to help you make this connection.

5.3.2 Measure Amplifier Offset Voltage (TA Demonstration)

(c) Ground both inputs of the amplifier, and measure the output offset with the digital multimeter. Record this value on the Data Sheet.

Detailed Procedure for Measuring Amplifier Offset Voltage

Using two short jumpers from the drawer of the station, ground the inputs of the amplifier by shorting sockets (i) C and D and (ii) G and H. Using a pair of banana-plug patch cords, connect the amplifier outputs P and Q to the voltage inputs of the DMM. Turn on the power supply for the amplifier, and measure the output offset. Record this value on the Data Sheet.

5.3.3 Measure Common-mode Gain (TA Demonstration)

(d) Using the 5-VDC power supply on the patch panel, apply 5 V to both inputs of the amplifier. Measure the output with the digital multimeter, and compute the common-mode gain in dB. Record the measurement and calculated value on the Data Sheet. Remove the 5 V from the inputs of the amplifier.

Detailed Procedure for Measuring Common-mode Gain

(i) Make sure the power to the patch panel is off, and then connect socket C to the red +5 VDC "HI" output socket on the patch panel using a banana-plug patch cord.
(ii) Next use one of the short jumpers from the drawer to connect sockets C and G.
(iii) Using a second banana-plug patch cord, connect the +5 VDC "LO" output socket of the patch panel to socket D (ground) on the amplifier circuit board.
(iv) Using a pair of banana-plug leads, connect the voltage inputs of the multimeter to the 5-V power supply sockets.
(v) Power on the amplifier and patch panel, and measure the power supply voltage using the "DC V" function of the multimeter.
(vi) Record this value on the Data Sheet as V_{in}.
(vii) Turn both power supplies off.
(viii) Connect the amplifier outputs to the voltage inputs of the multimeter, power on the amplifier, and measure the output with the patch-panel power supply *off*.
(ix) Record this value on the Data Sheet as V_{off}.
(x) Turn the patch-panel power supply on, and record the new voltage on the Data Sheet as V_{on}.
(xi) Using these data, determine the common-mode rejection ratio of the amplifier.
(xii) Record these values on the Data Sheet. Note that the common-mode rejection ratio of this amplifier is very high and difficult to measure accurately with the current setup.
(xiii) Turn off the power to the patch panel and the amplifier. Remove the jumper, and disconnect the leads between the amplifier and the patch panel.

5.3.4 Measure Normal-mode Gain of Amplifier

(e) Remove all external resistors from the instrumentation amplifier board. Locate the nominal 1-kΩ gain resistor mounted to a dual banana plug. Measure its resistance using the digital multimeter, and compute the expected gain using the equation

$$G_{calc} = 1 + \frac{49.4\ \text{k}\Omega}{R_G}$$

Record the resistance and calculated gain on the Data Sheet. Install the gain resistor between RG1 and RG2.

(f) Program the function generator to produce a 30-Hz sine wave with an amplitude of 100 mVp-p and an offset of 0 V. Apply this waveform to the input of the amplifier. Use both the oscilloscope and the DMM to measure the input and output waveforms. The oscilloscope will be used to just check that both the input and the output signals look correct. The DMM will be used to measure the RMS voltage level of the two wave forms. Note you can only measure one waveform at a time with the DMM. Calculate the gain from the ratio of the amplitudes. Record the measurements and calculated values on the Data Sheet.

Detailed Procedure for Measuring Normal-mode Gain

(i) Program the function generator to produce a 30-Hz sine wave with an amplitude of 100 mVp-p and an offset of 0 V. Ask your Assistant for help if needed.
(ii) Using a BNC-to-banana-plug adapter and two banana-plug patch cords, connect the output of the frequency generator to the voltage inputs of the digital multimeter. Measure the RMS output of the generator using the "AC V" function of the multimeter. Record this value on the Data Sheet.
(iii) Transfer the banana-plug leads from the multimeter to the inputs (sockets C and G) of the amplifier. Using a pair of banana-plug patch cords, connect the output of the amplifier to the voltage inputs of the digital multimeter.
(iv) Turn on the amplifier power supply, and measure the RMS voltage of the output. Compute the gain and the gain error with respect to the calculated value. Record this information on the Data Sheet.

5.3.5 Determine Amplifier Specifications from Data Sheet

(g) Using the specification sheets for the AD620AN instrumentation amplifier given in Appendix C (available in complete form at www.analog.com), determine the typical and guaranteed gain error, offset voltage, and common-mode rejection ratio. Record these values on the Data Sheet. Compare your measurements with these values, and note any discrepancies.

5.4 Frequency and Decay Constant of Vibrating Beam

5.4.1 Measure Beam Length and Compute Natural Frequency

(a) Locate the cantilever beam apparatus on the bench top, and measure the beam length using the tape measure provided. For this determination, exclude the length of any screw protruding from the free end but include half the support thickness at the fixed end. The collar where the beam and support come together makes the measurement slightly more difficult, but it is otherwise unimportant. Record the beam length on the Data Sheet, and compute the natural frequency using the following equation based on our analysis of beam vibration.

$$\omega_{n,calc} = 0.14\ \frac{D}{L^2}\sqrt{\frac{E}{\rho}}\ 2\pi$$

5.4.2 Setup the Strain Gage Bridge

(b) Place the two bridge completion resistors (≈350Ω) across socket pairs A-B and C-D.

(c) Install the 4.7-kΩ resistor in its proper position.

(d) Connect the two strain gages on the cantilever beam across socket pairs E-F and G-H.

Detailed Procedure for Connecting Strain Gages

One gage is mounted on the top of the beam, and the other is mounted on the bottom. The two leads for each gage have the same color connector. For example, if two yellow and two blue connectors are on the harness coming from the beam, then one pair (yellow, for example) should be connected to sockets E and F, and the other pair (blue) should be connected to sockets G and H. Some of the beams have a fifth black connector to the shield of the cable. We will not be using this connector so leave it disconnected.

(e) Connect the output of the amplifier to the voltage inputs of the DMM. Power on the amplifier, and measure its output using the "DC V" function. Using a small screwdriver, adjust the potentiometer to zero the bridge output voltage. Try to get a value between -1 mV and +1 mV. If this is not possible, get as close to zero as possible.

5.4.3 Program the Oscilloscope

(f) Transfer the output of the amplifier to oscilloscope Channel 1.

(g) Program the oscilloscope as follows:

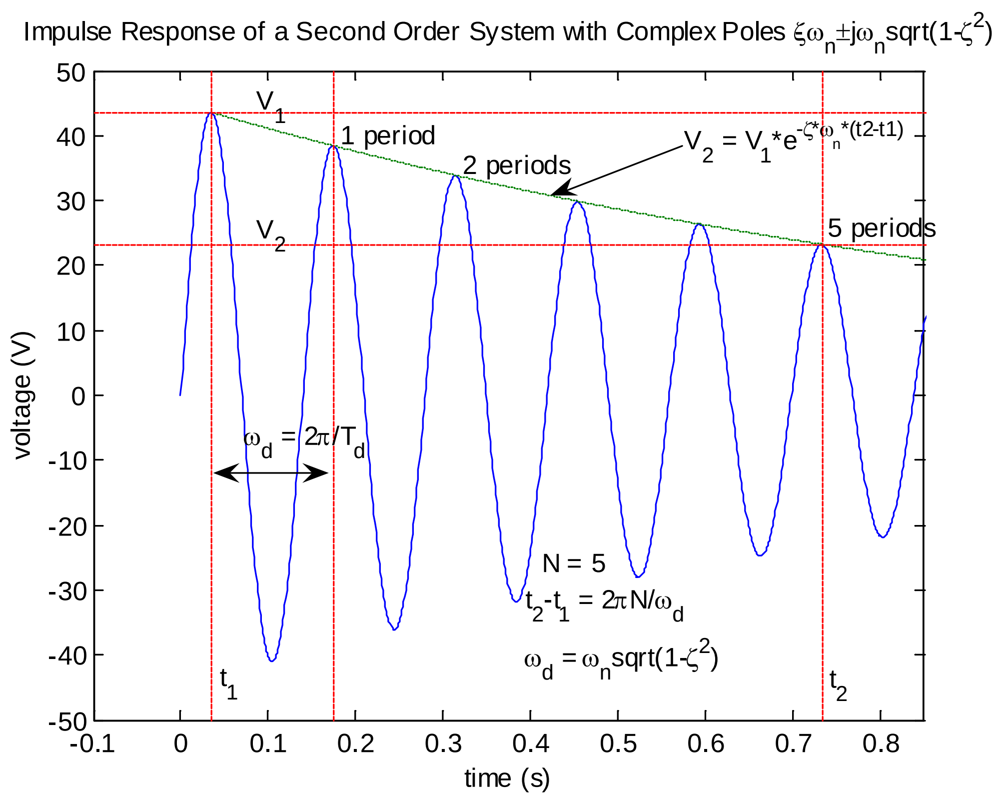
(i)	Vertical scale:	50 mV/div
(ii)	Horizontal scale:	20 ms/div
(iii)	Channels:	Channel 1 on; DC coupling; BW lim on; invert and vernier off; Channel 2 off
(iv)	Trigger source:	Channel 1
(v)	Trigger mode:	normal; level = ≈20 mV
(vi)	Trigger slope/coupling:	positive, DC, HF rejection on, noise rejection on

(h) Make sure the "RUN" mode indicator appears in the upper right-hand corner of the screen.

5.4.4 Measure Natural Frequency and Damping Ratio of Beam

(i) Strike the beam sharply but gently with your finger. The goal here is make the beam vibrate producing a damped oscillation waveform similar to the one shown below. A glancing blow may work best, and a faint tone may be audible when a "good" strike is achieved. Obtaining the proper waveform may require some trial and error. Also, adjust the oscilloscope settings as needed. Once a good trace is generated, press the "STOP" key.

(j) Locate two peaks roughly five oscillation periods apart as shown below, and use the oscilloscope cursors to measure the time and voltage levels of each peak. Record these values on the Data Sheet along with the Δt and frequency ($1/\Delta t$) values. Use this data and the equations given in the figure below to calculate the natural frequency and damping ratio.



5.4.4 Use the Instrumentation Amplifier to measure the small voltage from a Thermocouple.

In this section you will demonstrate to your TA that you have understood how to use this instrumentation amplifier. There are no items in the data sheet to fill out. Just show your TA the oscilloscope displaying the voltage of the thermocouple.

(a) Setup the instrumentation amplifier so that it has a gain of 1000. Figure out the gain resistance and ask your TA for that size of resistor.

(b) Connect the thermocouple to the amp board so that an increase in temperature increases the voltage output. (Remember that “Low” is red for this style of thermocouple.)

(c) Use the oscilloscope to measure the output.
(d) Demonstrate it working to your TA.

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 377 Ω. Conversely, the electric field will be "greater" if the load impedance is more than 377 Ω. 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 power = I_{RMS}*V_{RMS}, V_{RMS} = I_{RMS}*R and AC power = (V_{RMS}* 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 377 Ω.

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 $r \le \lambda$ 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 ($r \le \lambda$); electric field dominates	electric or capacitive coupling
near field ($r \le \lambda$); 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 1st 4 items, Electromagnetic 2nd 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.

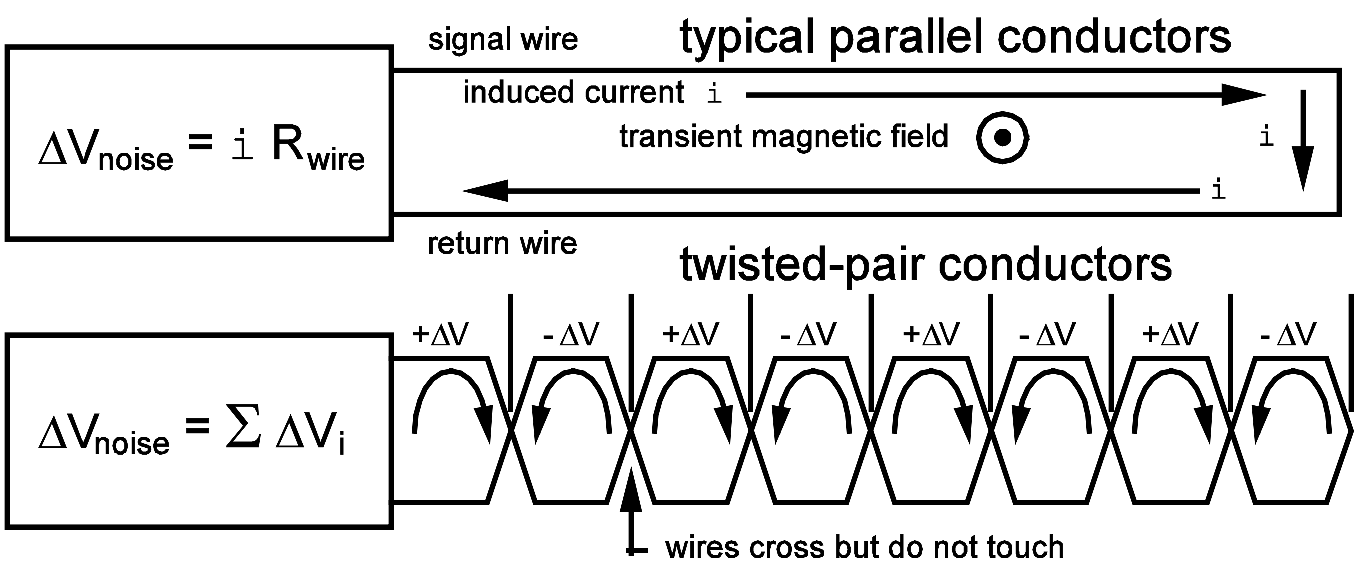


Figure A.1 Magnetically-coupled Interference in Parallel-conductor and Twisted-pair Cabling.

APPENDIX B. BEAM VIBRATION

In this experiment, we shall also study the vibration characteristics of a cantilever beam. Two strain gages 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	$M \frac{d^2y}{dt^2} + D \frac{dy}{dt} + K\, y(t) = F(t)$
Parametric Form of Governing Equation	$\frac{d^2y}{dt^2} + 2\, \zeta\, \omega_n \frac{dy}{dt} + \omega_n^2\, y(t) = f(t) = \frac{F(t)}{M}$ $\omega_n = \sqrt{\frac{K}{M}} \qquad \zeta = \frac{D}{2\, M\, \omega_n}$
Damped Oscillations	$y(t) = \frac{y_o \exp(-\zeta\, \omega_n\, t) \sin(\omega_d\, t + \phi)}{\beta} \quad \frac{D}{2\, M\, \omega_n}$ $\omega_d = \beta\, \omega_n \qquad \beta = \sqrt{1 - \zeta^2} \qquad \phi = \arccos(\zeta)$

Table B.2 Summary of Beam Vibration Analysis.

Dimensional Governing Equation	$m' \frac{\partial^2 y}{\partial t^2} = - E I \frac{\partial^4 y}{\partial x^4} + F'(x,t)$
Dimensional Boundary Conditions	$y(0,t) = 0 \qquad \frac{\partial y}{\partial t}\bigg\rvert_{x=0} = 0 \qquad \frac{\partial^2 y}{\partial t^2}\bigg\rvert_{x=L} = 0 \qquad \frac{\partial^3 y}{\partial t^3}\bigg\rvert_{x=L} = 0$
Nondimensional Governing Equation	$\frac{\partial^2 y_*}{\partial t_*^2} = - \frac{\partial^4 y_*}{\partial x_*^4} + F_*(x_*,t_*)$
Nondimensional Boundary Conditions	$y_*(0,t_*) = 0 \qquad \frac{\partial y_*}{\partial t_*}\bigg\rvert_{x=0} = 0 \qquad \frac{\partial^2 y_*}{\partial t_*^2}\bigg\rvert_{x=1} = 0 \qquad \frac{\partial^3 y_*}{\partial t_*^3}\bigg\rvert_{x=1} = 0$
Definitions of Dimensional Variables	x = position t = time y = beam displacement m' = beam mass per unit length F' = distributed force per unit length E = modulus of elasticity L = beam length h = beam thickness b = beam width I = moment of inertia of beam cross sectional area = $bh^3 / 12$
Definitions of Nondimensional Variables	$x_* = x / L \qquad y_* = y / L \qquad t_* = t \sqrt{\frac{E\, I}{m\, L^3}} \qquad F_* = \frac{L^3\, F'}{E\, I}$
Series Solution	$y_*(x_*,t_*) = \sum_{k=0}^{\infty} A_k\, \Psi_k(x_*) \exp(-j\, \omega_k\, t_*)$
Vibration Modes	$\psi_n(x_*) = \cosh(\lambda_k x_*) - \cos(\lambda_k x_*) - D_k [\sinh(\lambda_k x_*) - \sin(\lambda_k x_*)]$ $D_k = \frac{\cosh(\lambda_k) + \cos(\lambda_k)}{\sinh(\lambda_k) + \sin(\lambda_k)}$
Vibration Frequencies	$\omega_k = B_k \sqrt{\frac{E\, I}{m\, L^3}} \qquad f_k = C_k \sqrt{\frac{E\, I}{m\, L^3}} \qquad B_k = (\lambda_k)^2 \qquad C_k = \frac{\lambda_k^2}{2\, \pi}$
Eigenvalue Equation	$\cos(\lambda) \cosh(\lambda) = -1$ λ_k are roots; $\lambda_k \approx (2\, n + 1)\, \pi / 2$
Spring Constant	$K = 3 \frac{E}{I\, L^3}$

Table B.3 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	6.9×10^{10} N / m^2
Beam Density (aluminum)	ρ	2700 kg / m^3
Moment of Inertia of Beam Cross Sectional Area	$I = \pi D^4 / 64$	1.277×10^{-9} m^4
Actual Beam Mass	$m = \rho \pi D^2 L / 4$	0.120 kg
Spring Constant of Beam	$K = 3 \frac{E}{I L^3}$	6165 N / m
Effective Beam Mass	$M = 0.2427 \times m$	0.029 kg
Natural Frequency for Fundamental Vibrational Mode	$\omega_{k,o} = B_o \sqrt{\frac{E I}{m L^3}}$	461 rad / s
Natural Frequency of Fundamental Vibrational Mode	$f_{k,o} = \frac{\omega_{k,o}}{2 \pi}$	73 Hz

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.