Data Acquisition and Measurements

LABORATORY MANUAL

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CHAPTER

1

MEASUREMENTS AND DATA ANALYSIS

1.1 Measurements

Experimentation and the design of measurement systems are primary activities for many technical professionals. In practice, engineering measurements occurs in two primary categories. The first is where new information is being sought. The second involves monitoring and controlling processes, such as in automation systems. In either case, performing engineering measurements are not as simple as turning on equipment and reading the numbers.

Properly run experiments follow the scientific method, listed as:

I. **Define the purpose**
The key to running a successful experiment is to ask “What am I looking for?” A clear and concise purpose must be identified and considered during the entire experiment. An example is: *“The purpose of this test is to determine the center of gravity of a Head FXP tennis racket”.* For many tests, the purpose is already defined. The person designing and conducting the tests must constantly consider the purpose.

II. **Form a hypothesis**
Predicting the outcome allows equipment to be properly selected and identifies the critical parameters that must be controlled. A hypothesis should be formed from technical insights and deductive reasoning.

III. **Plan the experiment**
In planning an experiment, one must decide on the physical event that must be measured to acquire the desired measurement. For example, if the density of parts must be obtained, the engineer must decide the properties that can be measured, and equipment necessary.

A second important decision in planning an experiment is deciding on the necessary equipment. A schematic of a general measurement system is shown in Fig. 1.1. A sensor, which may require power, is necessary to detect the physical event. An understanding of the features and limitations of the many sensors commercially available is important. The output of the sensor may need to be modified and put into a usable form, which is called signal conditioning. Signal conditioners, which require power, typically amplify and eliminate unwanted noise from the sensor signal. Lastly, the signal must be recorded and displayed, in a step called data acquisition.

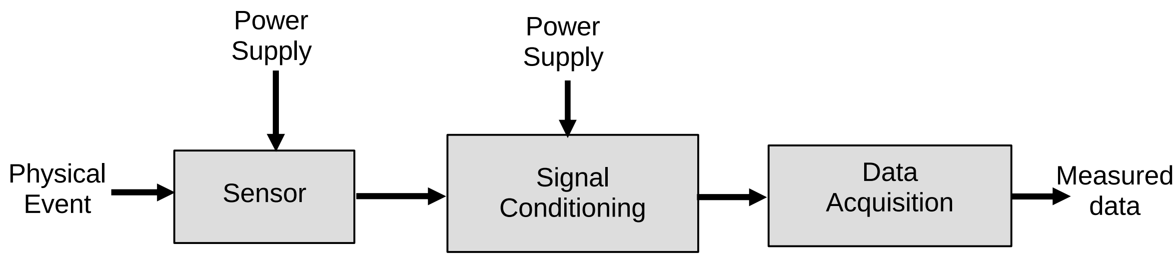


Figure 1.1 Generalized measurement system

Another important decision in the planning of an experiment is identifying the variables that need to be control, such as room temperature, humidity, surface finish of test piece, angle of contact with sensor, etc. Controlling variables can complicate tests and is expensive. Therefore, the controlled variables should be carefully considered.

IV. Collect the data

Collecting data is often the tedious portion of conducting a test. Care must be taken to remain focused and avoid mistakes. The primary decision is the number of data points that should be obtained. As a guideline, 30 are consisted statistically optimal, 15 are usually statistically valid, and 10 is statistically considered a minimum.

V. Analyze the data

Data must be examined for consistency. No matter how hard one tries, there will be some data points that appear to be grossly in error. Data points that do not follow commonsense consistency and do not appear proper should be eliminated. For example, if heat is added to a container, and a particular data point indicates a lowering temperature, that point should be eliminated. If several points fall in this category, the test should be repeated.

Legitimate data must be reviewed to determine a format that provides a revealing and concise summary. Much consideration must be taken to decide an ideal manner to present the results. Statistics should always be used to summarize.

VI. Form a conclusion

The data should be carefully, and meticulously, examined. Any observations and trends should be cited. Specific, quantifiable, conclusions must be drawn. This is the real "value added" from the technical professional. An attempt to utilize technical knowledge to explain the trends and conclusions is expected.

VII. Report the experiment
The results of a test must be documented, along with the specific test parameters and methods. This is necessary to preserve the and serve as evidence of decisions that were made using the test results.

1.2 Statistical Analysis of Experimental Data

Measurements usually introduce a certain amount of variability and randomness into the results. After numerous data points, x_i, are acquired, a statistical summary must be presented to simplify further analysis and make decisions. The primary statistical measures describe the location of the data (or central tendency), the dispersion (or spread), and the accuracy. An illustration of statistical summary measures for a set of data is given in Fig. 1.1.

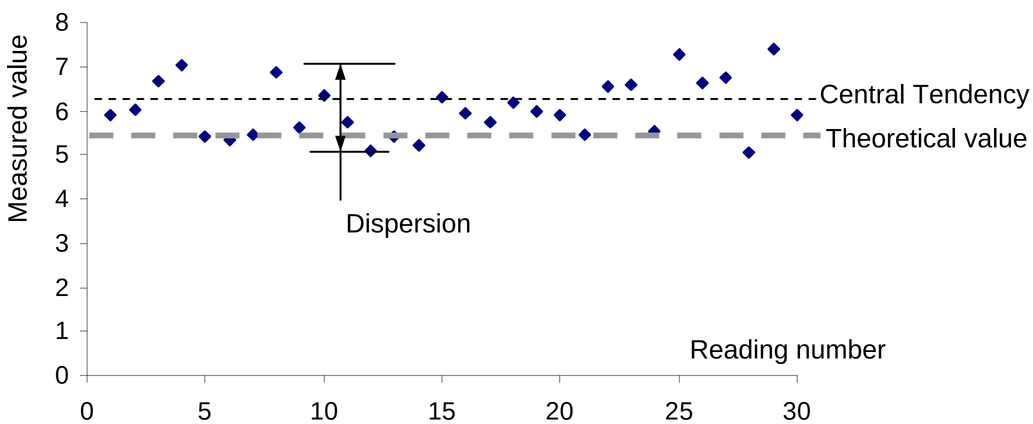


Figure 1.1 Experimental data

Measures of Central Tendency

Mean or average, $\bar{x}$, is the balance point for the data (center of mass). It is the most common method to measure of location of data. It is calculated as

$$\bar{x} = \frac{x_1 + x_2 + \ldots x_n}{n} = \frac{1}{n}\sum_{i-1}^{n} x_i \qquad (1.1)$$

Another measure of central tendency is the median, $\tilde{x}$. The medial is the middle, or fiftieth percentile, data point. It is determined by arranging the data in ascending order then locating the middle point. If the data set contains an even number of data points, the median is the average of the two central values.

Numerically based software, such as Excel or LabVIEW, can be used to efficiently organize data and to determine the average and median for a series of data points.

Measures of Dispersion:

Dispersion is a measure for the spread of a set of data. The range, R, is the difference between the maximum and minimum values.

$$R = x_{\max} - x_{\min} \tag{1.2}$$

Standard deviation measures the average distance between each point and the mean. Engineering experiments involve samples of the entire population. The sample standard deviation, s, is appropriate and calculated as

$$s = \sqrt{\frac{1}{(n-1)}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{1.3}$$

Again, numerically based software, such as Excel or LabVIEW, can be used to efficiently determine the minimum and maximum data points, and calculate the standard deviation.

Measures of Accuracy

Accuracy is determined from a theoretical value or an established standard or baseline. Accurate measurements have low error. Absolute Error, e , is used to directly compare the measure data with a standard and calculated as

$$e = x_{theory} - \bar{x}_{measured} \tag{1.4}$$

Percent Error, $\%e$:, is a relative measure and calculated as

$$\%\, e = \frac{e}{x_{theory}} = \frac{x_{theory} - \bar{x}_{measured}}{x_{theory}} \tag{1.5}$$

Graphical Summary

Tables and graphs have always constituted the most powerful and effective way of communicating the information in a set of data.

Tables are useful for summarizing categories of data. An example of tabular data summary is given as Table 1.1

Table 1.1: Weight of American Coins (g)

	Penny	Nickel	Dime	Quarter
Avg	2.501	5.003	2.268	5.670
Std. Dev	0.128	0.406	0.203	0.448

A useful bar graph is shown in Fig 1.2 and called a histogram. The horizontal axis of a histogram has equal increments of values that span the data set, called bins. The vertical axis gives the number of data points occurring in each bin. A histogram provides a visual representation of the grouping, or density of a data set.

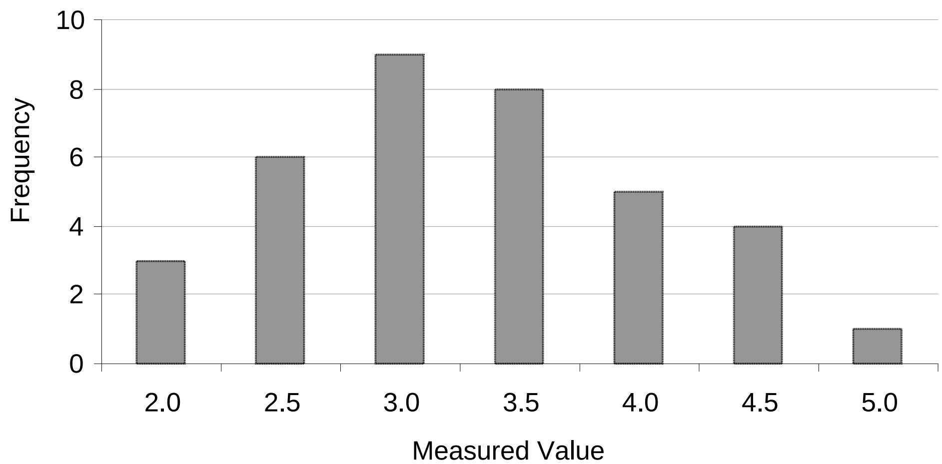
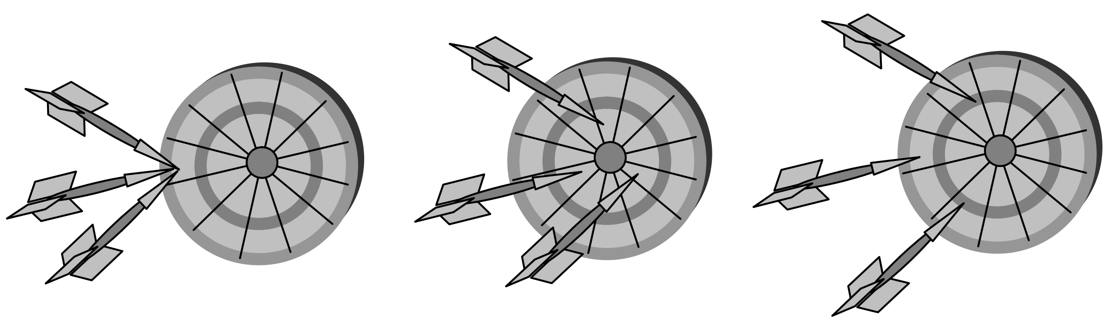


Figure 1.2 A histogram

1.3 Classifications of Measurement Error

Errors in experimental data generally fall into three categories: bias errors, precision errors, or illegitimate errors. These three types of errors are illustrated with dart boards in Fig. 1.3. The type of error usually can be detected from the statistical summary of the data. Attempts should be made to minimize all error. Understanding the type of error usually gives clues to the cause, and the actions that can be taken to minimize it.



(a) Bias (b) Precision (c) Illegitimate

Figure 1.3 Error classification

Bias (or systematic) errors are consistent, repeatable errors. They are distinguished by a large difference between the average of the data and the true value. They are categorized by a high error and low dispersion. An example is a bathroom scale that always reads 10 lbs. too heavy. Bias errors are usually caused by poor equipment calibration, consistent human error, or built-in errors from the measurement system design.

Precision errors exhibit a lack of consistency. They are categorized by a low average error, but high dispersion. Precision errors are usually associated with insufficient sensitivity of the measuring system of varying environmental conditions.

Illegitimate errors are a result of outright mistakes. They are categorized by a high error and high dispersion. As the name suggests, these errors should not exist. They are caused by incorrect equipment usage, environmental disturbances that are so large that they hide the actual test information, or lack of care while conducting the test. If illegitimate errors are detected, the test should be stopped until the mistake is identified and eliminated.

1.4 Statistical Inference

A normal, or Gaussian, distribution describes a data set subjected to variations that are symmetrically scattered. It is often called the **bell curve** because a graph of its resembles a bell as shown in Fig. 1.4. It is symmetrical about the mean, $\bar{x}$, and the shape is determined by the standard deviation, s. A normal distribution frequently occurs in the physical world, and many engineering measurements can be assumed to resemble a normal distribution..

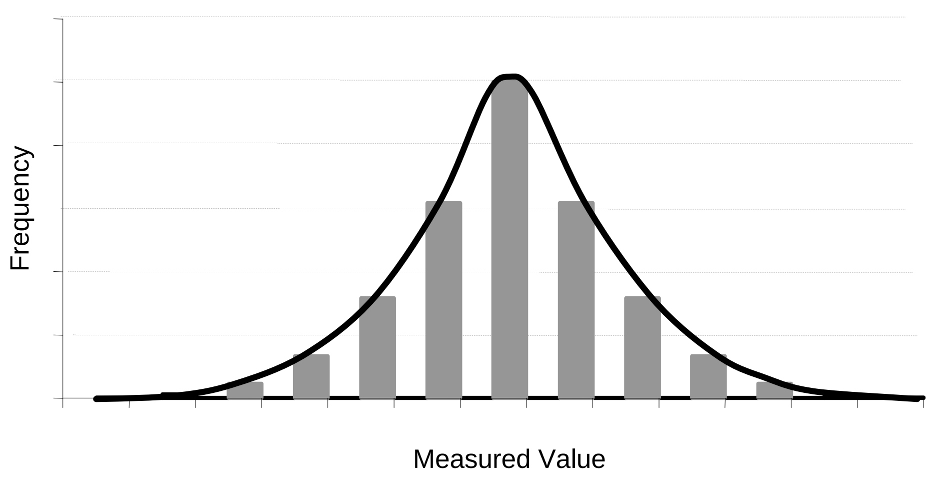


Figure 1.4 Normal distribution

An important function of statistics is to use the information from a data set to predict the behavior of the population. For example, after testing the time it takes for 10 light bulbs to fail, it is possible to determine the probability that another will fail prior to a certain time. This deduction is called statistical inference.

Using the mathematical development of a normal distribution, probability tables are constructed. One is given in Table 1.2, where

$$X = \bar{x} + Zs \tag{1.6}$$

The probability that a single value, x, will be lower than a value , X, is designated as $P(x<X)$. The parameter Z relates the probability to the statistical values $\bar{x}$ and s.

As an example, it is desired determine the volume in a pop can, from a particular filling station, where only one percent will have less liquid. Notice from Table 1.2 that a value with 1% of the population being lower is associated with Z=-2.328. Tests on 15 samples from that filling station show an average volume of 13.3 oz., with a sample standard deviation of 0.64 oz. Therefore, it is estimated that 1% of pop cans will have less than X = 13.3+(-2.328)(0.64) = 11.81 oz.

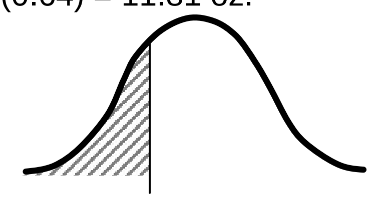


Table 1.2 Normal distribution

$P(x< X)$	Z	$P(x< X)$	Z	$P(x< X)$	Z
0.50%	-2.575	15.0%	-1.035	90.00%	1.281
1.00%	-2.328	20.0%	-0.842	92.50%	1.439
1.25%	-2.240	25.0%	-0.625	95.00%	1.645
2.50%	-1.960	50.0%	0.000	97.50%	1.960
5.00%	-1.645	75.0%	0.625	98.75%	2.240
7.50%	-1.439	80.0%	0.842	99.00%	2.328
10.0%	-1.281	85.0%	1.035	99.50%	2.575
12.5%	-1.150	87.5%	1.150		

1.5 Correlation of Experimental Data

Virtually all measured quantities are a function of one or more independent variables. For example, the coefficient of friction is dependant on the two contacting materials, their surface finish, and whether lubrication is present. These variables should be “controlled” during testing.

Many experiments involve the measurement of one parameter, as a control variable is changed over a range of values. The correlation between measurements that are dependant reveals important information. For example, a tension test on a material speciman is performed by applying an increasing amount of force and monitoring the resulting deflection. A classic stress-strain curve is shown in Fig. 1.5.

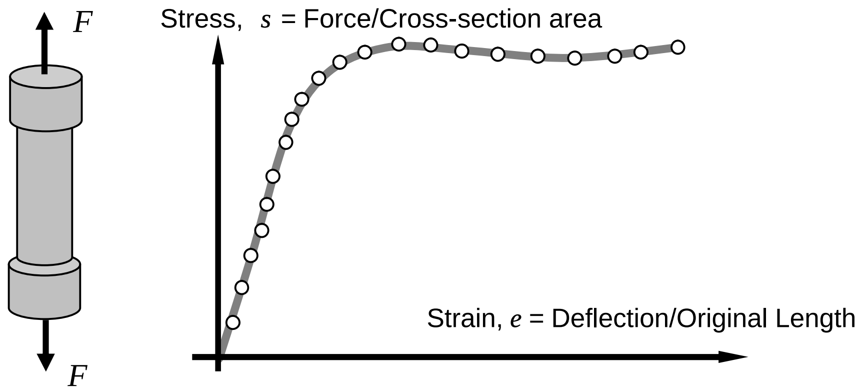


Figure 1.5 Dependency of test data

As a control variable is changed, statistical summary information, such as average and standard deviation are meaningless. Often, it is the relationship between these quantities which is of interest. For example, Modulus of Elasticity, *E*, is the slope of the linear portion of a stress-strain curve.

Least Squares Fit

For n test data points, where a linear relationship between a measured value, y, and a control value, x, is appropriate, the classic form of a straight line is used

$$y = m\,x + b \tag{1.7}$$

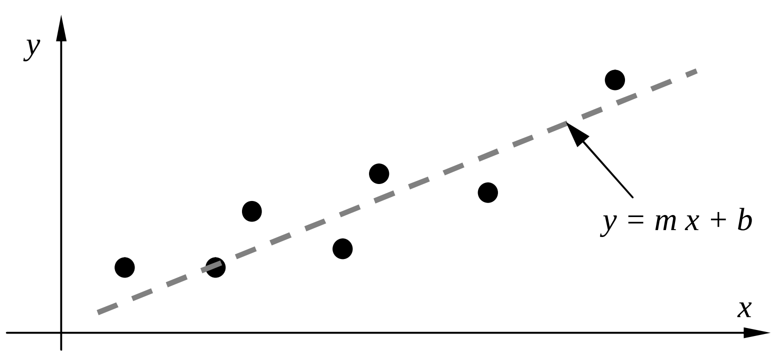


Figure 1.6 Normal distribution

A least squares fit is a mathematical formulation that statistically determines a relationship, which minimizes the distance between the trend line and the experimental data. This formulation for a produces a slope, m, of

$$m = \frac{n\sum(x_i y_i) - \left(\sum x_i\right)\left(\sum y_i\right)}{n\sum(x_i)^2 - \left(\sum x_i\right)^2} \tag{1.8}$$

and intercept, b, as

$$b = \frac{\left(\sum y_i\right)\sum(x_i)^2 - \left(\sum x_i\right)\left(\sum(x_i y_i)\right)}{n\sum(x_i)^2 - \left(\sum x_i\right)^2} \tag{1.9}$$

The coefficient of determination, r^2, is an indicator of the "closeness of fit". For $0.95 < r^2 < 1$, the regression can be considered a reliable fit. It represents the precent of the data that is closest to the best fir line. For example, if $r^2 = 0.850$, that means that 85% of the total variation in y can be explained by the linear relationship between x and y (as described by the regression equation). The other 15% of the total variation in y remains unexplained.

Linearity

Linearity error is a measure of how linear the best-fit of a sensor's calibration data. Non-Linearity, e_L, is usually reported as a percentage deviation relative to the maximum dependent variable (Full Scale Output, or FSO). Non-linearity is graphically depicted in Fig. 1.7

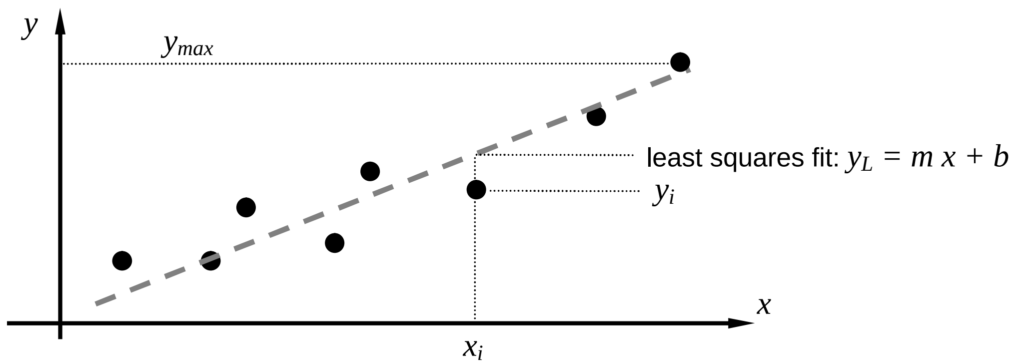


Figure 1.7 Non-linearity

Non-linearity is calculated as

$$e_L = 100\frac{|y - y_L|_{\max}}{y_{\max}} \qquad (1.10)$$

Non-linearity is commonly stated as in the form: ±0.5% of FSO

1.6 Presentation of Results: The Lab Report

It is commonly stated that all is lost if results are not documented. This section provides an outline of typical report format.

1. **Summary**
   The summary section is short, usually a maximum of two pages, including tables and charts. It should give a general picture of the laboratory experiments performed. It should be carefully planned to convey a wealth of information in a few pages. By reading the summary, the casual reader should get a clear idea of the scope and limitations of the entire experiment. It is typically the only portion of the report reviewed by

management, and is frequently detached from a detailed report to form an executive report. Therefore it must stand on its own and not refer to information in the detailed portion of the report. The summary is comprised of the following three subsections sections:

1.1 Purpose
This concisely (one or two sentences) states the objective of the experiments included in the report. These have been explicitly stated during each lab test.

1.2 Summary Results
A summary of the main experimental results included in the summary results section. Tables or charts usually work best in providing the maximum amount of information in a small space. Care should be taken in formatting the tables. They should not appear as spreadsheets squeezed into a report. The summary results need to directly address the purpose of the tests. A statistical analysis should be used to summarize the data.

1.3 Conclusions
The conclusion section should go hand-in-hand with the purpose. It uses the results given in the previous section to respond to the purpose. It should explain the trends encountered, errors found and theories proved. This section should also speculate on reasons for the observations and the causes of any significant errors found in the data.

2. Background And Theory
The background and theory section should include a survey of information that a technical reader needs to know in order to understand and appreciate the remainder of the report. It should also present any theoretical information and equations applicable to the experiments, or handling the results. Key terms should be defined and critical lab equipment should be introduced. Outside references are expected to be consulted in writing this section.

It is rather easy to go off the deep end in this section because with most technical subjects, there are great volumes of background and previous work. The writer should be wise to keep this section focused, yet complete. Expect your reader to have some technical background.

3. Equipment And Procedure
Sufficient information must be supplied on the apparatus and experimental procedures for the reader to understand exactly the method

and testing that was performed. This should include a complete list of equipment used (including makes and model numbers). Neat and professional sketches and annotated pictures greatly enhance this section.

Also include a step-by-step procedure. Be specific with the exact steps, and order of activities engaged during the tests. For example, “weights were placed on the scale, starting with 5 lbs, adding an additional 5 lb, and then an additional 10 lb”. It is best describe the procedures as a numbered list, as opposed to explaining in paragraph form.

4. **Detailed Results And Discussion**
   Results of the experiments, including all data (for example, density should not be solely reported, but also present the mass and volume of a sample) should be given in this section. Calculations are not to be shown. Clear tabular and graphical presentations should be used as much as possible to avoid a "wordy" discussion. Of course, some verbal discussions of the graphs and tables must be given to focus the reader on the salient features of the data. Once the results have been presented, they must be interpreted. The background, theoretical presentation and the results must all be tied together with the discussion.

5. **References**
   Cite the references explored and when direct quotes were used. Proper footnoting procedures should be followed.

Reporting Guidelines
The following list provides general style guidelines for preparing a technical report.

- The report must be presented in a professional format.
- Pay close attention to using correct English, spelling and grammar.
- A technical report should be written in third person, using past tense.
- Identify each section by its number and start a new page for each section.
- Use only 8-1/2 x 11 paper in your report. No fold out pages are to be used.
- Never plagiarize without citing a reference.
- Keep the summary brief (no more than 2 pages).
- Paste all tables and charts into the Word document. Do not include spreadsheet printouts attached to the report.
- Display an appropriate number of decimal digits.
- Every variable and symbol must be defined.

- Always cite units for all values.
- Keep the same font and size of text in tables, equations and paragraphs.
- Center tables on the page. Don't go out into the margins.
- Use statistical techniques to properly report results, adding credibility to the numbers.
- Number and title each figure, table and graph. Refer to the figure number when referring to the figure, etc.
- Plot a curve fit trend line (not always linear) through data points in a graph. Don't connect the dots.
- Never include any actual calculations in the report.
- Always compare (by calculating percent error) your results with applicable theory/handbook values.
- Provide a plausible explanation based on scientific principles wherever possible.
- Define any equations that you intend to use, when analyzing results, in the background section. This includes percent error.
- Include equations in the text and use equation numbers for easy reference. For example:

$$F = m\,a \qquad (1)$$

- Use a detailed list to identify specific steps in your experimental procedures.
- Include pictures of the experimental set-up, and screen shots of data acquisition programs.

Pre-Lab Exercises:

1-1. As a general rule, how many data points should be taken for a test to be statistically valid.

1-2. The purpose of a test is to measure the density of several samples. Determine physical properties that can be measured, and necessary equipment.

1-3. The purpose of a test is to measure the efficiency of a water heater. Determine the physical properties that can be measured, and necessary equipment.

1-4. Tensile tests were conducted on several steel samples, taken from the same lot. The ultimate strength of 20 samples is given below.

Ultimate Strength:	44	56	52	57	46
(ksi)	54	49	46	60	56
	48	61	55	53	52
	62	59	49	51	58

Handbooks state that the material has a ultimate strength of 55 ksi. Use Excel to determine the:

a) Mean
b) Median
c) Maximum Value
d) Minimum Value
e) Range
f) Sample Standard Deviation
g) Absolute Error
h) Percent Error

1-5. Create a histogram for the data given in the previous problem.

1-6. Specify the type of measurement error that is associated with data that has a low standard deviation, but a high percent error. List possible causes.

1-7. Specify the type of measurement error that is associated with data that has a high standard deviation, but a low percent error. List possible causes.

1-8. Hardness tests of several samples of a steel samples, taken from a typical lot, give an average of 305 Bhn and sample standard deviation of 12 Bhn. Determine the hardness:

(a) where 90% of all parts are lower.
(b) where 10% of all parts are greater.
(c) where 25% of all parts are greater.
(d) where 75% of all parts are greater
(e) values that will capture 90% of all parts, equally distributed around the average.

1-9. Use the least squares method to determine the modulus of elasticity from the data given below, obtained from a tension test.

Stress (psi)	Strain (in/in)
5000	0.0004
10000	0.0011
15000	0.0015
20000	0.0021
25000	0.0024
30000	0.0029
35000	0.0035
36000	0.0055
37000	0.0083
38000	0.0240
40000	0.0520

Laboratory Experiences:

For all measurements given in experiences 1-1, through 1-6, perform the following tasks:

a) Use Excel to statistically summarize the data.
b) Use Excel to plot a frequency distribution.
c) Compute the error from the expected (standard) value.
d) Comment on the variation.
e) Categorize the type of error and identify possible causes.
f) Assuming a standard deviation, statistically determine:
   - The low and high values that would contain 50% of the population, equally distributed around the mean.
   - The value that 5% of the population will be lower.
   - The value that 90% of the population will be greater.
   - The value that 85% of the population will be greater.
g) As always, return all equipment and clean you work area.

1-1. Determine the variation inherent in measuring resistor values. Obtain several of the same type resistors and use the benchtop multimeter to measure their resistance value.

1-2. Determine the variation in dimensions on #6-32 hex nuts. values. Obtain several nuts and use calipers to measure the distance across the flats, which should be 0.309 in.

1-3. Determine the variation in coefficient of friction measurements (m?= Pulling force/Normal force) between dry and oily surfaces. Handbooks list the following standard coefficient of friction values:

	$m_{steel/steel}$		$m_{alum/alum}$	
	Clean	Oily	Clean	Oily
Static	0.80	0.16	1.30	0.30
Dynamic	0.40	0.03	0.40	0.10

1-4. Determine the variation in density measurements (r = Mass/Volume). Obtain several samples of the same material and measure the density of each. Handbooks list the following standard density values:

r_{steel} = 0.283 lb/in^3
$r_{aluminum}$ = 0.100 lb/in^3
r_{brass} = 0.304 lb/in^3

Conversions:
1 ml = .061 in^3
1 g = .0022 lb

1-5. Determine the variation in fishing line strength measurements. Prepare several samples from the same spool and measure the breaking strength. Use the advertized value on the spool as the standard.

1-6. Determine the variation in coefficient of restitution measurements

(r = Ö $\overline{\text{Bounce height/drop height}}$).

Obtain a ball and measure the coefficient of restitution, repeating several times. Handbooks list the following standard values:

$r_{golf\ ball}$ = .858 $\qquad$ $r_{rubber\ ball}$ = .752
$r_{tennis\ ball}$ = .712 $\qquad$ $r_{glass\ marble}$ = .658

1-7. Determine the spring constant of a coil spring, which is derived from the slope of measured data points.

a) Measure the deflection of the helical extension spring at several (at least 15) loads. Spend some time thinking about your loading procedure.
b) Using Excel, plot the displacement vs. load.
c) Use a linear curve fit to determine the "spring" constant.
d) Compute the r^2 and percent non-linearity.
e) Comment on the "closeness" of the fit, along with possible reasons for any non-linearity.
f) Calculate a theoretical spring constant and comment on difference between theoretical and experimental stiffness.

$$k = \frac{GD_W}{8C^3N}$$

where:

G = Shear Modulus (G_{steel} = 11.5 x 10^6 psi)
D_W = Wire Diameter
C = Spring Index = $\frac{D_M}{D_W}$

D_M = Mean Coil Diameter = OD - D_W
N = Number of Coils in Spring

1-8. Determine the spring constant of a bungee cord, which is derived from the slope of measured data points.

a) Measure the deflection of the bungee cord at several (at least 15) loads. Spend some time thinking about your loading procedure.
b) Using Excel, plot the displacement vs. load.
c) Use a linear curve fit to determine the "spring" constant.
d) Compute the r^2 and percent non-linearity.
e) Comment on the "closeness" of the fit, along with possible reasons for any non-linearity.
f) As always, return any equipment and clean your workstation.

CHAPTER

2

ELECTRICAL CIRCUITS AND MEASUREMENTS

2.1 Electrical Circuit Components and Properties

Most measurements involve converting a mechanical property to an electrical signal. A fundamental understanding of the common quantities and electrical circuits is in order.

A resistor is a two terminal electronic component that opposes flow of electricity. Resistance, R, quantifies the opposition and is specified in Ohms (Ω). The symbol is shown in Fig 2.1.

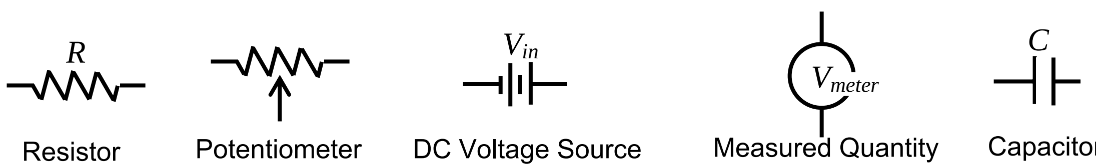


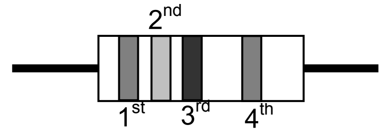
Figure 2.1 Electrical circuit element symbols

The value of a resistor is indicated by color bands on the component. It consists of four colored bands that are painted around the body of the resistor. Three bands are spaced closer together than the fourth. Each color has an associated value. The first two bands give the first two significant digits of the resistance value, the third is a number-of-zeroes, and the fourth is the tolerance accuracy of the value of the value. Colors values used in the first three bands are shown in Table 2.1. The fourth band is either brown (1%), red (2%), gold (5%), or silver (10%). If the fourth band is omitted, the tolerance is 20%.

As an example, green-blue-yellow-silver is 560 kΩ ± 10%. The first band, green, has a value of 5 and the second band, blue, has a value of 6, and is counted as 56. The third band, yellow, has a value of 4, which adds four 0's to the end, creating 560,000Ω at ±10% tolerance accuracy. Of course 560,000Ω reduces to 560 kΩ ±10%.

Table 1.2 Resistor Color Codes

Color	Value
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Gray	8
White	9



A potentiometer is resistor with a third terminal attached to a sliding contact that can move along the resistor. The resistance across two of the tree terminals is changed as the wiper is repositioned. Potentiometers can be used as variable resistors to control electrical devices, such as a volume adjustment, or can be used as position sensors, as in a joystick. The symbol for a potentiometer is shown in Fig 2.1.

DC voltage source is supplied by a battery or power supply. The symbol for a DC voltage source is shown in Fig 2.1. A time varying voltage can supplied by a function generator.

A measured quantity is obtained with a multimeter, oscilloscope, or data acquisition system. The symbol for a measured quantity is also shown in Fig 2.1.

In resistive circuits, Ohm's Law is the primary relationship used to determine the electrical values. The voltage, V, across a resistor is related to the current, I, through the resistor by

$$V = I\ R \qquad (2.1)$$

The electrical power, P, dissipated a resistor is

$$P = I\ V = \frac{V^2}{R} = I^2\ R \qquad (2.2)$$

Since electrical circuits involve interconnected resistors, it is convenient to combine them into an equivalent value. The total resistance of N resistors combined in series as

$$R_T = R_1 + R_2 + \ldots + R_N \qquad (2.3)$$

A capacitor is a two terminal electrical component that stores electrical energy. They are commonly used in filter, or attenuate noise. Capacitance, C, is a measure of electric charge stored and is specified in Farads (F). The symbol of a capacitor is shown in Fig 2.1.

A inductor is a two terminal electrical component that resists changes to current. They are commonly used in filters and transformers. Physically, an inductor is formed as a conducting wire shaped into coils. Inductance, L, is a measure of the ability to store magnetic energy and is specified in Henry (H).

Impedance is a derived property that measures the opposition of a device to an alternating current. It extends the concept of resistance to AC circuits. Impedance, Z, is dependent on the resistance of a device, along with the capacitance and inductance and is specified in Ohms (Ω).

An LED, or light emitting diode, is a device that is an electronic light source shown in Fig 2.2. When the diode is switched on, energy is released in the form of light. Unlike incandescent lights, an LED will only light with correct electrical polarity. Also, since an LED has little resistance, directly connecting to a power source will induce a large current and damage the LED. Therefore, they should be used in series with a current limiting resistor.

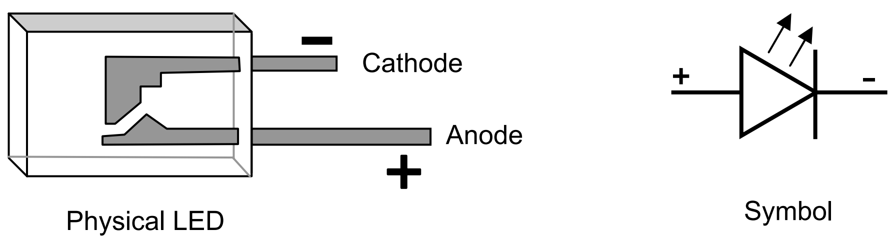


Figure 2.2 Light Emitting Diode

A transistor is a semiconductor device that can be used to amplify or switch electrical signals. A voltage or current supplied to one set of terminals changes the current flowing through the other set of terminals. An NPN transistor is shown in Fig. 2.3. A voltage applied to the base causes a large amount of current to flow from the collector to the emitter. Thus, a small amount of control current can be used to switch a large current to drive high load components. This strategy will be used to large devices such as motors, with small computer generated signals.

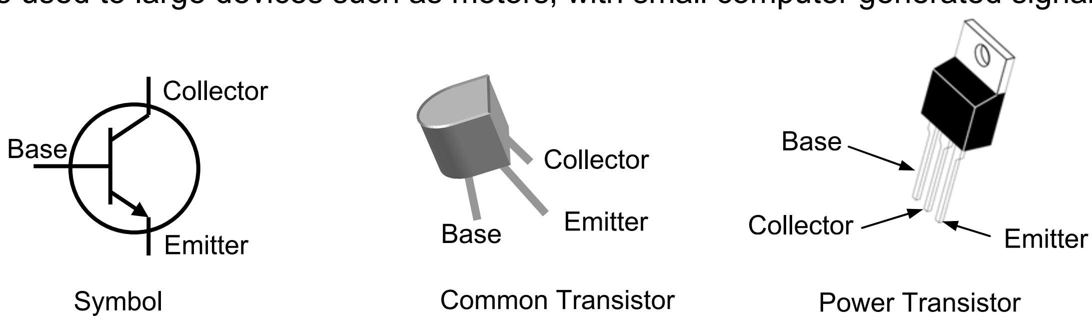


Figure 2.3 NPN transistor

2.2 Breadboards

A breadboard, or proto-board, is a reusable, solder-less device used to build a prototype electronic circuit. It is widely used to construct laboratory instrumentation circuits necessary to perform mechanical measurements.

The board is configured with a series of perforations The perforations are arranged in a series of rows and columns. The perforations are spaced 0.1 inches apart. This spacing is consistent with the pins on standard integrated circuit chips. Dual inline packaged (DIP) chips can be inserted to straddle the center block.

Each perforation has a spring clip designed to secure a 22 gage (AWG) solid copper wire. The connectivity of the perforations is shown in Fig. 2.4.

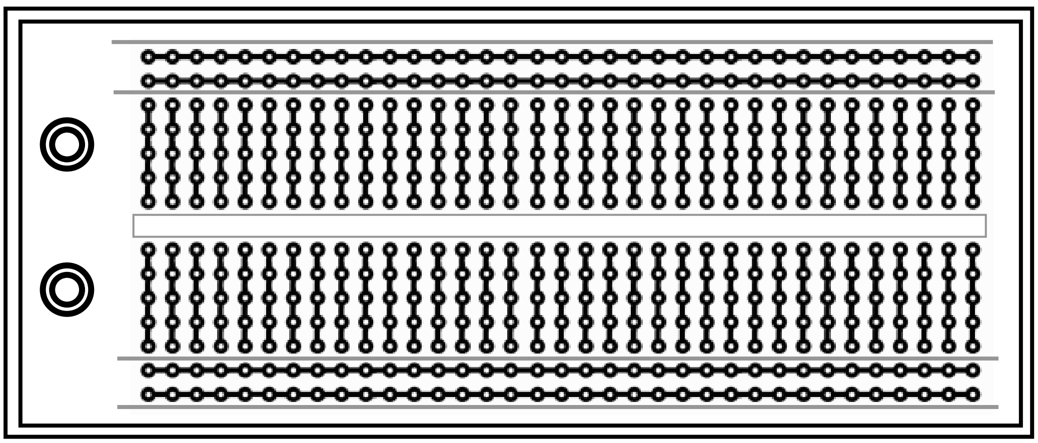


Figure 2.4 Breadboard construction

2.3 Electrical Instruments

Power Supply
A power supply provides DC voltage and current operate electrical circuits and other devices. A Tektronix PS-283 DC power supply is shown in Fig. 2.5

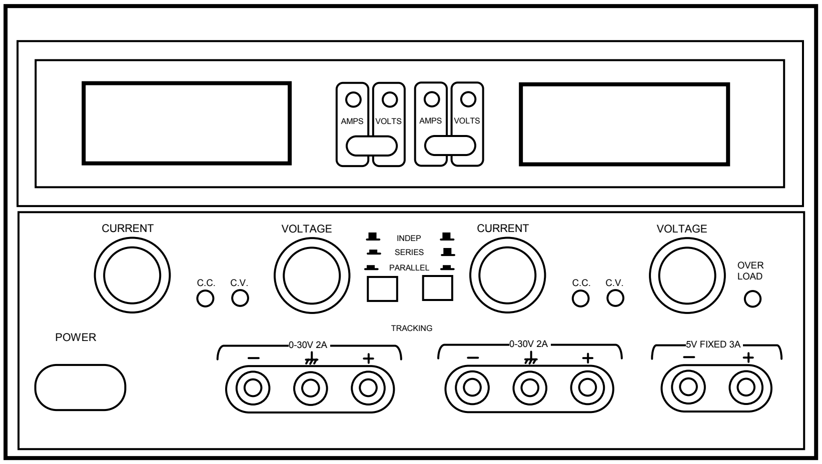


Figure 2.5 Tektronix Power Supply

This unit has two independent power supplies, CH1 (left) and CH2 (right), each having positive (+) and negative (-) output terminals. A center ground terminal can be used to provide a datum reference in a circuit. Both supplies have a voltage and current control knobs. The green CV light is on when the channel is being limited by the voltage control. The red CC light is on when the channel is being limited by the current control. Some models display output voltage and amperage. Others have a switch to toggle between voltage and current display.

The two push button tracking switches allow the unit to be operated in different modes:

- When both tracking switches are out, the unit is in an independent mode and CH1 and CH2 power supplies are completely independent from each other.
- When the left tracking switch is in and the right switch is out, the unit is in the series mode. The voltage of both supplies are combined and set with the CH1 voltage control. To use the unit in this mode of operation, the positive terminal (red) of CH2 is connected to the negative terminal (Black) of the CH1 supply. A jumper is usually placed between the joined terminals and ground. Voltage is added to allow the two supplies to be used in an additive fashion. A power supply used in this mode is shown in Fig 2.6.
- When both switches are in, the unit is operating in a parallel mode. The CH1 and CH2 supplies are wired together in parallel. The two uptuts can be used to double the current capability.

An online user’s manual should be consulted for further details.

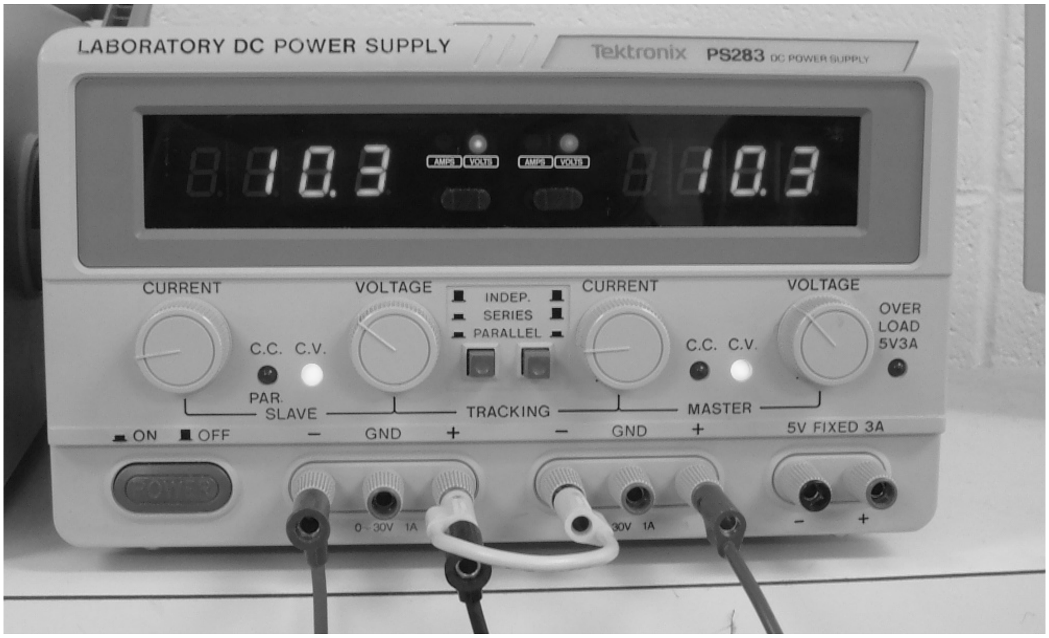


Figure 2.6 Power Supply in Series mode

Function Generator

A function generator is a device which produces electrical waveforms. The common forms are a sine, square and triangle. The device has controls to adjust the waveform amplitude, frequency and offset. A Wavetek generator, model 25, is shown in Fig. 2.7. A brief description of the capabilities is given below. The output is accessible with a 600 Ω or 50 Ω impedance.

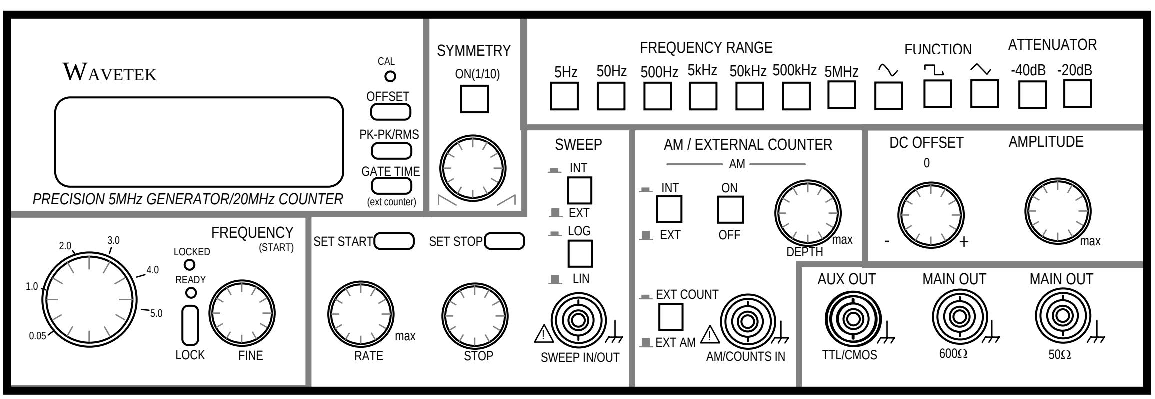


Figure 2.7 Wavetek Model 25 Function Generator

The function selection buttons controls the form of output wave between sinusoid, square, and triangle.

The frequency range selection buttons indicates the maximum frequency range of the output signal. So if a 1 kHz signal, it would be best to select the 5 kHz frequency range. Then frequency knob is used to adjust the frequency of the output.

The attenuator buttons are used to select the amplitude and DC offset range. The largest range occurs when both attenuators are off. The second largest is when only the -20 dB attenuator is on. The third largest is when the -40 dB attenuator is on, and the smallest range is when both attenuators are on.

To adjust the DC offset, push the offset button, then use the DC offset knob to change the value. Likewise, to change the amplitude, push the pk-pk/rms button and use the amplitude knob to set the amplitude.

Digital Multimeters

A Meterman bench multimeter, model BDM40, is shown in Fig. 2.4. Instructions for taking voltage, resistance and current measurements are given below. An online user's manual should be consulted for further details. Other digital multimeters operate in a similar fashion.

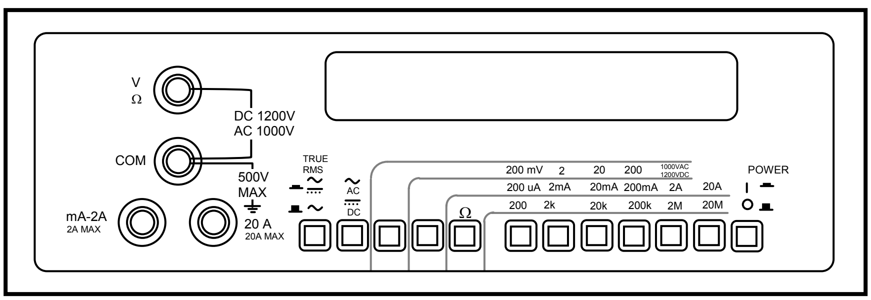


Figure 2.8 Meterman Digital Multimeter

To take voltage measurements, the black test lead should be plugged into the COMMON terminal and the red test lead into the V-Ω terminal. The controls and terminals used for making voltage measurements are located on the front panel. At the top left is the ACV/DCV switch. This pushbutton is interlocked with the other two white function selection switches A and Ω. If the DCV function switch is in the IN position, the meter is set to take DC voltage measurements. The light grey area around the ACV / DCV switch is extended up and to the right to enclose the five range values of the voltage function. Push the range switch immediately above the value to be measured. If the applied voltage is outside the selected range, the display will blink.

To take resistance measurements, the black test lead should be plugged into the COMMON terminal and the red test lead into the V-Ω terminal. The controls and terminals used to make resistance measurements are located on the front panel. The measurement function is selected by pushing the kΩ switch to the IN position. The colored area enclosing the kΩ function switch extends up and to the right enclosing the six range values for the resistance function. To select a particular resistance range, push the range switch immediately above the value to be measured. If the resistance is outside the selected range, the display will blink.

To take current measurements, the black test lead should be plugged into the COMMON terminal and the red test lead into the 2A or 20A terminal (depending on the expected of current). All of the controls and terminals used to make current measurements are located on the front panel. The AC mA and DC mA function switches determine the measurement function. The colored area around the 20A switch extends up and to the right to enclose the six range values for the 20A measurement function. Push the range switch immediately above the value to be measured.

It important to note that current is measured through a circuit, and never across a component. Failure to properly measure current will a blow a fuse or damage the multimeter. A circuit must be interrupted, and the meter leads inserted to take a current measurement. A schematic for properly taking a current measurement is shown in Fig. 2.3.

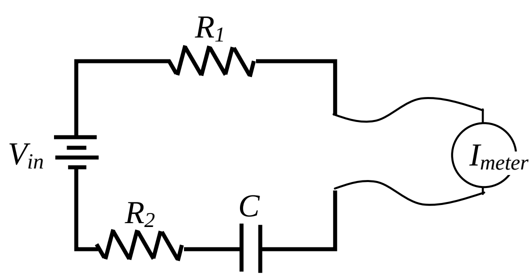


Figure 2.9 Obtaining a current measurement

Oscilloscope

If the output of a sensor is varying rapidly, a digital multimeter is not a suitable measuring instrument. An oscilloscope, which displays and analyzes traces of a signal, is more appropriate. An Agilent oscilloscope, model 54622D, is shown in Fig. 2.10.

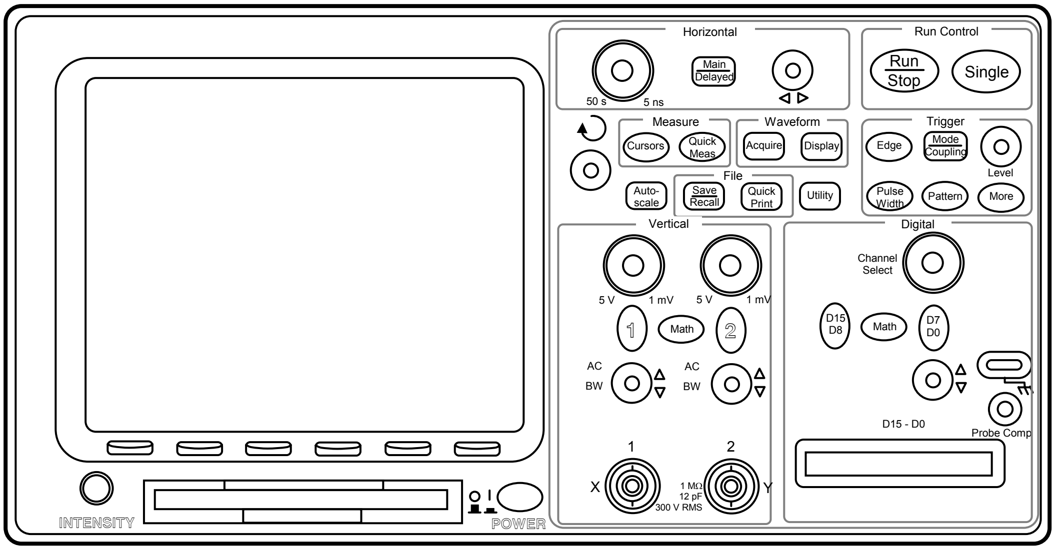


Figure 2.10 Agilent oscilloscope

The 54622D oscilloscope has two input channels, equipped with a BNC connector plugs. The input channels have 1 MΩ impedance, which minimizes the loading effect of the oscilloscope on the circuit under test.

The run/stop button can be toggled to continually display the input signal, or pause to view and perform analysis of the previous acquisition. A trigger event commands the scope to begin acquiring data. The oscilloscope will keep collecting data, since it analyzes signals that change with time. When Run/Stop is green the instrument is continuously acquiring data with the scope displaying multiple acquisitions of the same signal. When Run/Stop is red the oscilloscope has stopped acquiring data, and only information from the last trigger is available for display and measurement. Running in Single will cause the scope wait for the trigger event defined by the user and sweep one time.

To configure the instrument quickly, press the Autoscale key. Autoscale automatically configures the oscilloscope to best display the input signal by analyzing any waveforms connected to the channel inputs. Autoscale finds, turns on, and scales any channel with a repetitive waveform with a frequency of at least 50 Hz, a duty cycle greater than 0.5%, and an amplitude of at least 10 mV peak-to-peak. Any channels that do not meet these requirements are turned off.

The position knob (▲▼) moves the signal vertically. The vertical sensitivity can be changed with the large volts/division knob in the Vertical (Analog) section of the front panel. Notice that it causes the status line to change.

Turn the horizontal sweep speed (time/division) knob and notice the change it makes to the status line. Turn the delay time knob (◄►) and notice that its value is displayed in the status line.

The oscilloscope display contains channel acquisitions, setup information, measurement results, and softkeys for setting up parameters. The top line of the display contains vertical, horizontal, and trigger setup information. The display area contains the waveform acquisitions, channel identifiers, and analog trigger and ground level indicators. This measurements line normally contains automatic measurement and cursor results. The softkeys allow you to set up additional parameters for front-panel keys.

The most common softkey functions are invoked through the quick measure and cursors buttons. The keys on the front panel bring up softkey menus on the display that allow access to oscilloscope features. Many softkeys use the entry knob ↺ to select values.

2.4 Basic Circuits

The basic circuits used in instrumentation measurement circuits can be analyzed with two fundamental laws. Kirchkoff's current law states that current flowing into any junction of a electrical circuit must equal the current flowing out of it. Kirchkoff's voltage law states that the sum of voltage differences around any loop in an electrical circuit must equal zero. These laws are applied to common circuits used in instrumentation.

Voltage Divider
A voltage divider, as shown in Fig. 2.11, is commonly used to reduce the magnitude of a measurement signal.

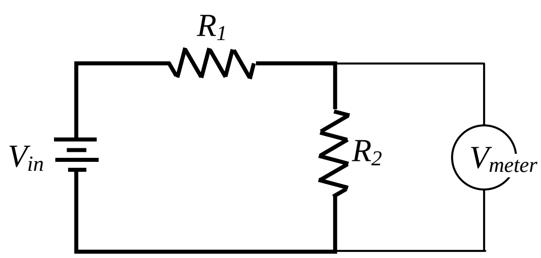


Figure 2.11 Voltage divider circuit

Being a series circuit, current through both resistors is identical. Ohms Law can be used to determine the voltage drop across R_2 as

$$V_{meter} = \frac{R_2}{R_1 + R_2} V_{in} \qquad (2.2)$$

Wheatstone Bridge
A Wheatstone bridge circuit, as shown in Fig. 2.12, is commonly used accurately measure small changes in electrical resistance. As will be presented in later chapters, this is very common in sensors for a variety of mechanical measurements. Detecting small resistance changes is accomplished by

balancing two legs of a circuit and taking a voltage difference measurement across the mid-span of the two legs.

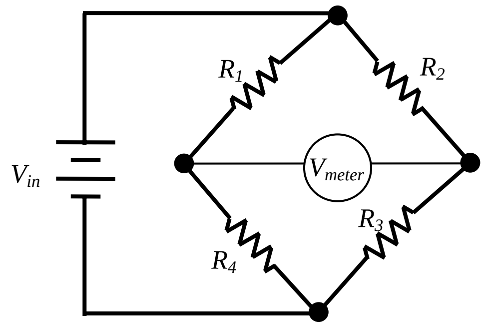


Figure 2.12 Wheatstone bridge circuit

The relationship between input voltage and measured voltage is

$$V_{meter} = \left(\frac{R_4}{R_2 + R_4} - \frac{R_3}{R_1 + R_3} \right) V_{in} \tag{2.3}$$

It is observed from Eq. 2.3 that if $R_1 = R_2$ and $R_3 = R_4$, then $V_{meter} = 0$. This is called a balanced bridge. As one resistance value changes due to a mechanical event (such as a temperature change), V_{meter} will reflect the change.

Balance Circuit

Because of manufacturing variation, a there will always be some difference between resistance values. Therefore, it is often desired to balance a Wheatstone bridge prior to taking measurements. This is the same concept as "zeroing" a bathroom scale prior to weighing oneself. A common circuit used to balance the output of a Wheatstone bridge shown in Fig. 2.13.

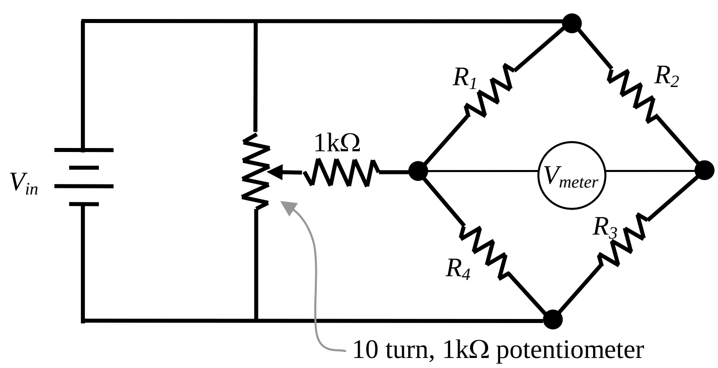


Figure 2.13 Wheatstone bridge balance circuit

2.5 Impedance Matching

Ideally, an instrument should not change the system that it is attempting to measure. A loading error is the difference between the true system value and the measured value. As a mechanical example, a very cold thermometer placed in a small amount of hot liquid may cool the liquid down while taking a temperature measurement. Because the intent was to measure the temperature of the liquid in its initial state, a loading error was introduced.

A loading error can occur whenever one circuit is attached to another. A common situation is shown in Fig. 2.14 where the output signal from one device provides input into a second device. Such a scenario is a voltmeter being connected to the output terminals on a power supply. Each device has its own impedance, Z. If the impedance of the second device (Z_2) is low, a current will flow in the loop formed by the two terminals, and place a load on the first device. The original voltage across the terminals differs from V_1 because of the load. If the second device is a meter, it has changed the of the first device producing s loading error.

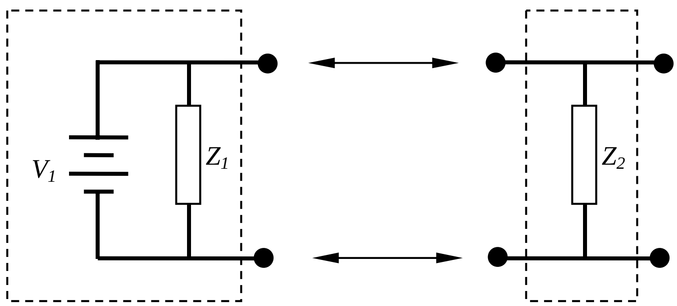


Figure 2.14 Connecting electrical devices

Loading errors can be avoided during measurement by considering the following recommendations. When measuring a voltage, the impedance of the measuring device should be much greater than the equivalent impedance of the source circuit. When measuring current, the impedance of the measuring device should be much lower than the impedance of the source circuit. In general, power supplies should have low impedance. Voltmeters should have a high impedance. Ampmeters should have a low impedance.

2.6 Operational Amplifiers

An amplifier is a device that scales the magnitude of an analog input signal according to the relation

$$V_{out} = G(V_{in}) \tag{2.3}$$

where the gain, G, is a constant that may be a positive or negative value. Of special interest for mechanical measurements is a solid-state instrumentation amplifier. Figure 2.14 shows an common commercial amplifier, INA11AP.

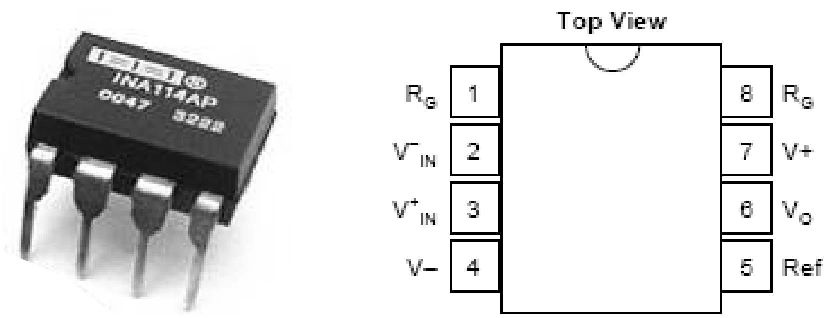


Figure 2.14 INA114AP Instrumentation Amplifier

The amplifier requires a dual polarity dc excitation power ranging from ±5V to ±15V. This excitation is applied to pin 7 and pin 8, as seen in the pin-out diagram of Fig. 2.14. A resistor is placed across pins 1 and 8 to set the gain according to

$$G = 1 + \frac{50\ k\Omega}{R_G} \tag{2.4}$$

The input signal that is to be amplified is sent into pins 3 and 2. The amplified signal will at be available at pins 6 and 5.

Many sensors produce low outputs signals. However, more accurate measurements can be made from meters when the signal is large. Amplification is important to increase the level of the measurement signal and increase performance of the instrumentation system. Amplification a key element to signal conditioning, mentioned in Chapter 1.

2.6 Filters

A fluid filter is a common device that removes impurities in a fluid as portrayed in Fig 2.15.

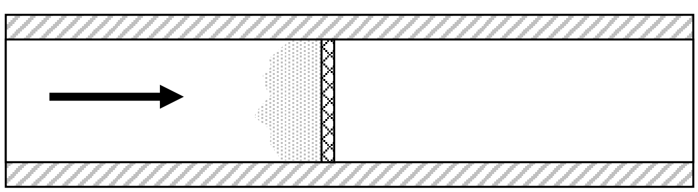


Figure 2.15 Fluid Filter

In an instrumentation system, a filter is used to remove undesirable frequency information from a dynamic signal. Their main function is to minimize the effects of noise and interference. They can be broadly classified as low-pass, high-pass, band-pass and notch. A low-pass filter permits signals with frequencies below a prescribed cut-off to pass, while blocking high frequency content. Conversely, a high-pass filter permits signals with frequencies above a prescribed cut-off to pass, while blocking low frequency content. A band-pass filter permits signals with frequencies between two prescribed values to pass, while blocking low and high frequency content. Lastly, a notch filter blocks frequencies between two prescribed limits.

A simple passive low-pass filter is constructed with a resistor, R_{LP}, and capacitor , C_{LP}, as shown in Fig. 2.16. This is termed a Butterworth filter circuit.

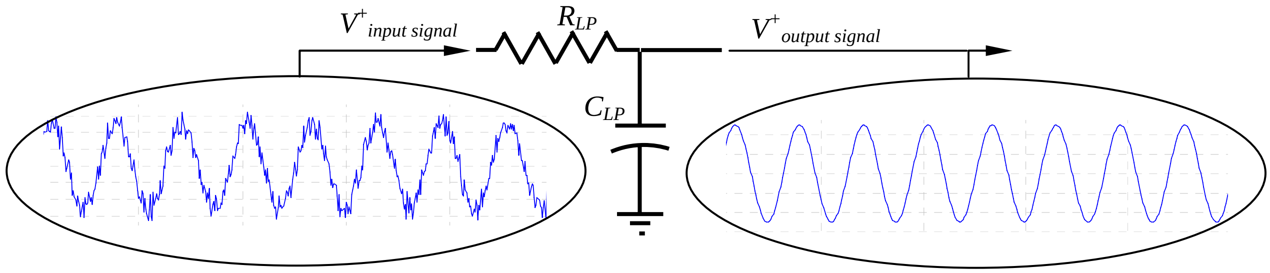


Figure 2.16 Low pass filter

The prescribed cut-off frequency, f_c, is set by the values of the resistor and capacitor through the relation

$$f_c = \frac{1}{2\pi\, R_{LP} C_{LP}} \tag{2.5}$$

An ideal cut-off filter can not be constructed with practical components. Instead, the magnitude of the signal through a real filter will “roll-off” relative to frequency. A low-pass response curve is shown in Fig. 2.17.

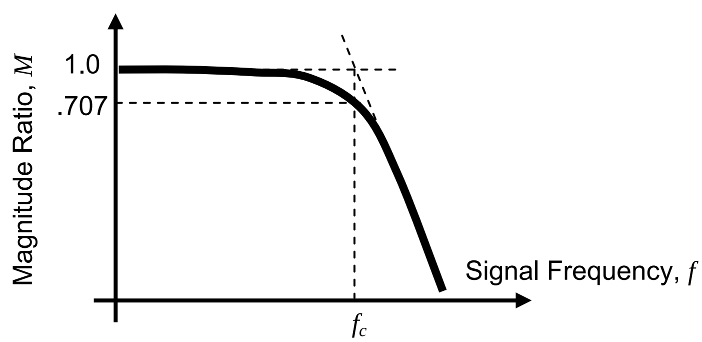


Figure 2.16 Low pass filter response curve

A magnitude ratio, M, is amount of total signal at a particular frequency, f, that passes through a filter. For the Butterworth low-pass filter, the magnitude ratio is calculated as

$$M = \frac{1}{\sqrt{1 + (f / f_c)^2}} \tag{2.6}$$

Figure 2.17 shows a physical low-pass filter set on a breadboard.

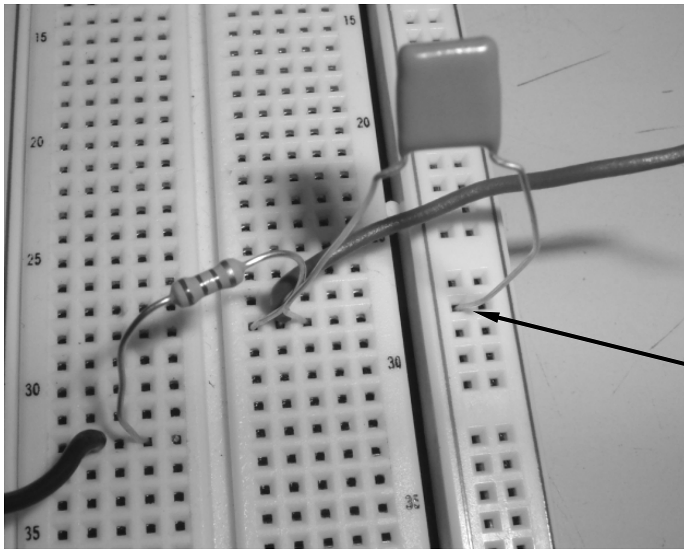


Figure 2.17 Physical low pass filter

2.6 Ground and Ground Loops

Because of the network of wires in an electric supply grid, ground is not an absolute value. Ground values vary between ground points because the return passes through different equipment or building wiring on its return path to earth. Thus, if a signal is grounded at multiple points, such as a power supply, an amplifier and a data acquisition device, the grounds could be at different voltage values.

Ground loops are caused by connecting a signal to two or more grounds that are at different voltages. With a ground loop, an electrical interference is superimposed onto the signal. A ground loop can manifest itself in various forms, such as a sinusoidal signal, or an offset. Always ensure that a system including its sensors and all electrical components have only one ground point.

Pre-Lab Exercises:

2-1. The bands on a resister are brown-red-brown-silver. Determine its resistance value.

2-2. What would happen to the amperage reading if a 20 Ω resistor added, in series, to a 100 Ω resistor?

2-3. What voltage can be placed across a 100 Ω resistor and not exceed 0.25W?

2-4. A 5 V supply is provided for an LED, whose current is limited to 200mA. Determine an appropriate resistor to place in series with the LED to limit the current.

2-5. A 10 V is supplied across a voltage divider circuit with a 500 Ω and 10 kΩ resistors. Determine the anticipated voltage drop across, and power dissipated in, the 500 Ω resistor.

2-6. A voltage divider circuit is to be used to reduce 10 V to 2.5 V. Determine appropriate resistor values if the power dissipation through either resistor does not exceed 0.25 watt.

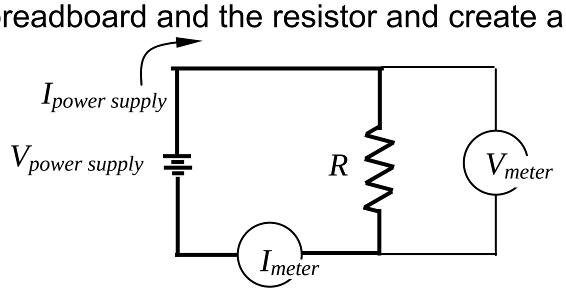
Laboratory Experiences:

2-1. Determine the accuracy of the power supply voltage display.

a) Use the benchtop and handheld multi-meters to measure the voltage from the power supply.
b) Compare the power supply readings with the meter by calculating the absolute error, and percent error.
c) Repeat the measurements at several different voltages (at least 15).
d) Calculate the average, minimum, maximum, range, standard deviation of the errors.
e) Comment on the results and the trends.
f) Assuming a standard deviation, statistically determine:
   - The absolute error (±) between the power supply and the bench-top meter that will capture 95% of all readings.
   - The absolute error (±) between the power supply and the bench-top that will capture 99% of all readings.
   - The percent error (±%) between the power supply and the bench-top that will capture 95% of all readings.
   - The percent error (±%) between the power supply and the bench-top that will capture 99% of all readings.
g) As always, return equipment and clean-up the workstation.

2-2. Determine the accuracy of the power supply current display.

a) Obtain a resistor (in the range of 300 – 800 Ω) and use the bench top multimeter to accurately measure its resistance.
b) Use a breadboard and the resistor and create a simple resistive circuit.



c) Use a handheld meter to measure the voltage across the resistor.

d) Use the bench top multimeter to read current through the circuit. Be careful with your set-up.
e) Using the measured resistance value, calculate the current through the resistor, and power dissipation.
f) Compare the power supply amperage with the meter amperage and the current calculated through the meter voltage reading. Calculate the absolute error and percent error.

$$e_1 = I_{P.S.} - I_{calculated}, \qquad e_2 = I_{P.S.} - I_{meter}, \quad e_3 = I_{meter} - I_{calculated}.$$

$$\%e_1 = 100\frac{\left(I_{P.S.} - I_{calculated}\right)}{I_{P.S.}}, \ \%e_2 = 100\frac{\left(I_{P.S.} - I_{meter}\right)}{I_{P.S.}}, \ \%e_3 = 100\frac{\left(I_{meter} - I_{calculated}\right)}{I_{meter.}}$$

g) Repeat the measurements at several different voltages (at least 10), and resistors (at least 3). Be cautious, as these are 0.125 watt resistors.
h) Comment on the results and the trends.
i) As always, return equipment and clean-up the workstation.

CHAPTER

3

INTRODUCTION TO LABVIEW

3.1 LabVIEW Basics

LabVIEW is an acronym for **Lab**oratory **V**irtual **I**nstrument **E**ngineering **W**orkbench. It is a program that is used to analyze data, much like Excel, VBA or Matlab. The primary difference is that LabVIEW uses graphical programming, where operations are visually connected with wires. LabVIEW programs are called virtual Instruments, or VIs for short. A basic VI is illustrated in Fig. 3.1.

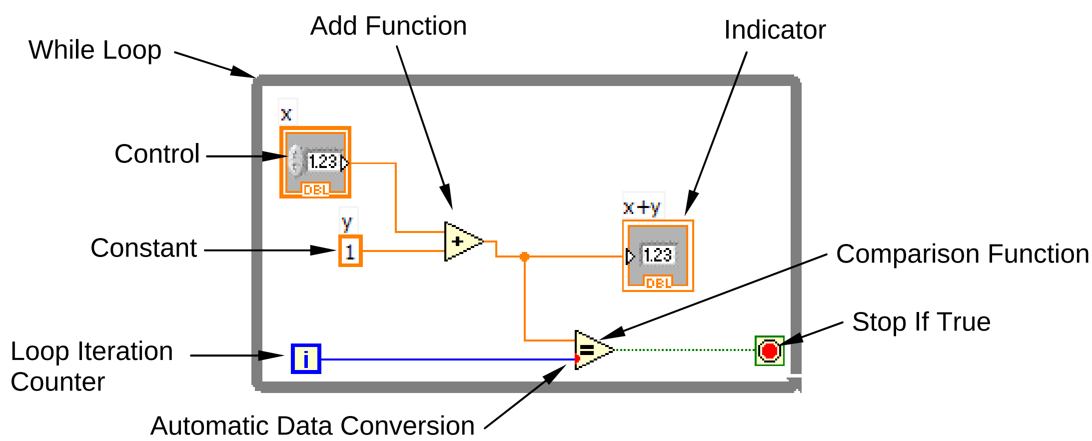


Figure 3.1 A basic LabVIEW program

LabVIEW is developed by National Instruments, a company that creates hardware and software products that focuses on computer technology in taking measurements, controlling processes and analyzing and storing data. The real strength of LabVIEW is the ease of external devices, specifically test sensors and automation equipment.

The basic program shown in Fig. 3.1 uses some simple functions, controls, indicators, and structures. The color and physical features of the line that connects the elements represents the data type being transferred.

3.2 The LabVIEW Workspace

Once starting LabVIEW, and selecting a blank VI from the Getting Started screen, two windows appear: the front panel and the block diagram. A single VI file will contain both windows. Tool and function palettes can also be made visible, as shown in Fig. 3.2.

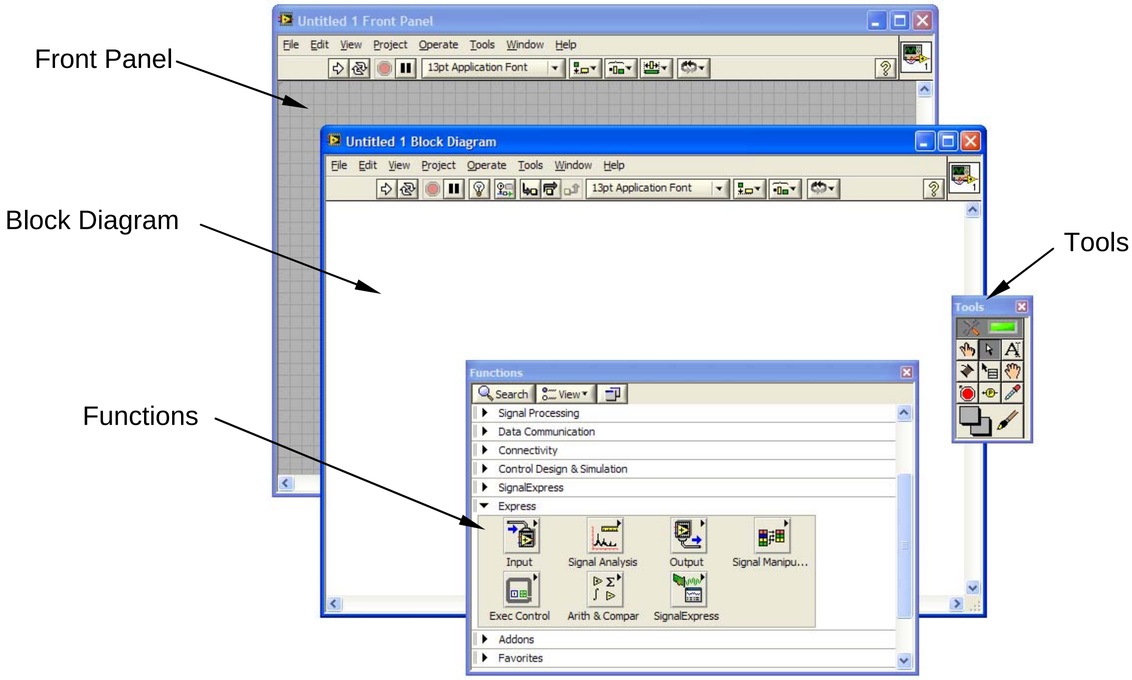


Figure 3.2 The LabVIEW workspace.

The tools, functions, and controls palettes are used in creating the program and are made visible through the View menu. The functions palette is visible only when the block diagram window is active. The controls palette is only visible when the front panel window is active.

The Front Panel

The Front Panel contains the human interface program input and output. Items such as gauges, switches, numbers, buttons, lights and plots are placed on the Front Panel. A Front Panel can be configured to appear as a benchtop meter, giving rise to the Virtual Instrument. An example is shown as Fig 3.3.

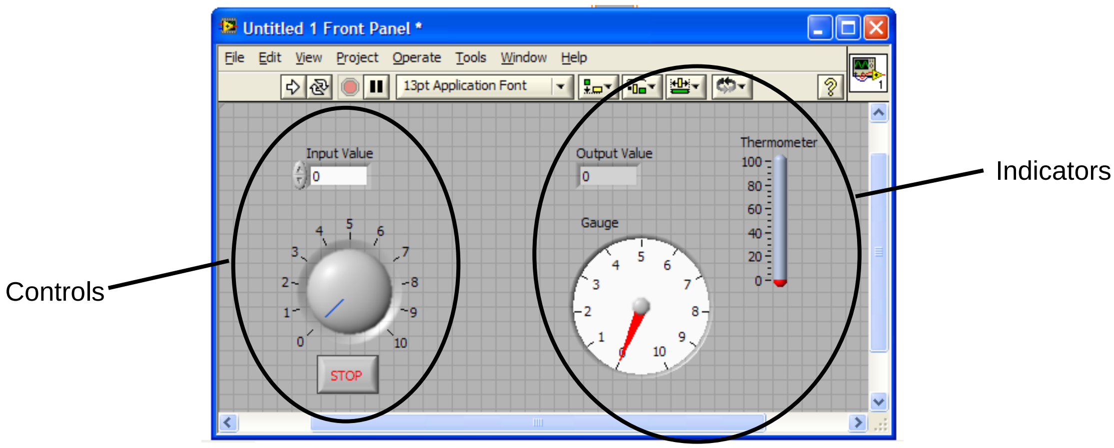


Figure 3.3 The front panel.

Regardless of the style, the front panel is a combination of controls and indicators. Controls is a LabVIEW term for program inputs, and indicators are program outputs. Controls and indicators are placed on the front panel by selecting them and “drag and dropping” them from the Controls palette. The Controls palette is shown in Fig. 3.4. Once an object is on the Front Panel, its size, shape and position can be adjusted.

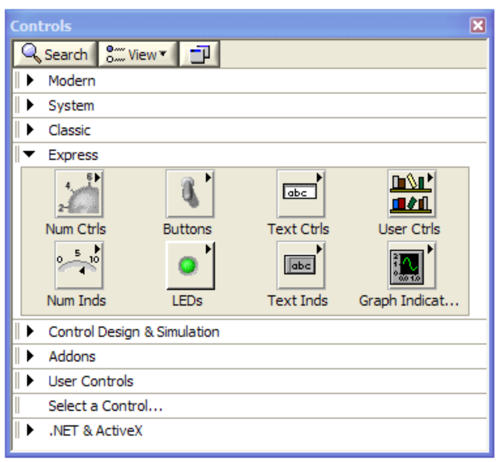


Figure 3.4 Express controls

The Block Diagram

The second window is the Block Diagram and contains functions that manipulate the input parameters and create output values. Items such as mathematical functions, signal analysis, comparison, iteration loops are placed on the block diagram. An example of a block diagram was shown in Fig 3.1.

The majority of functions and structures that are used for constructing data acquisition and measurements block diagrams are on the express palette, as shown in Fig. 3.4. Each icon that has a triangle in the upper right corner contains sub-palattes that are displayed once the top-level icon is clicked. As with the Front Panel, functions are placed on the front panel by selecting them and "drag and dropping" them from the Functions palette.

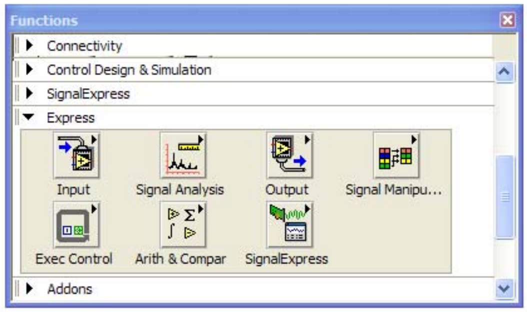
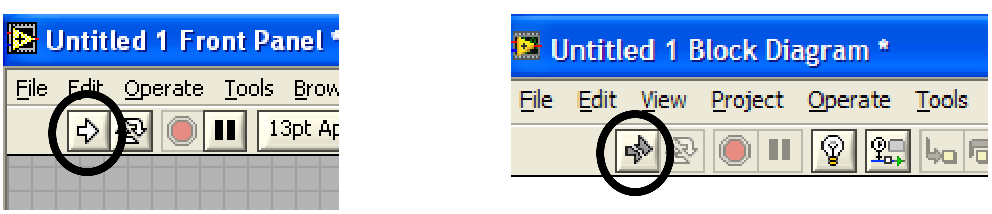


Figure 3.5 Express functions.

Each function has terminals that either lead into, or flows from the function. Terminals is a point to which a wire can be attached to pass data. Terminals that accept data have small black arrows that points into the function. Terminals that supply data have small black arrows that point out of the function. The color of the terminal corresponds with the data type that is passed. That is, if a terminal is orange, it will work with numeric data.

To wire two items together on the Block Diagram, select the spool of wire (Wire Tool) on the Tool palette. Position the spool over the terminal of the origin object (it blinks) and click once (do not hold). Move the spool over the destination terminal and click once. A wire, with the color consistent with the terminals, will connect the two terminals.

Once several objects are wired together, the Run button (arrow) on the top task bar will be complete as shown in Figure 3.6a. If the arrow is broken, as shown in Figure 3.6b, the VI is incomplete or has errors. To execute the VI, select the Select Tool (pointer) from the Tool palette and click the Run.



(a) (b)

Figure 3.6 VI Run Button.

3.3 VI Programming Fundamentals

Creating a VI to perform a desired task involves accepting the necessary controls (inputs), routing them through a series of operations and presenting the results to indicators (outputs). The following topics discuss commonly used functions and related pertinent programming information.

Basic Math

Mathematical operations can be completed by wiring controls to indicators through a series of math functions. Wiring can become complex and care should be taken to keep the neat. An example of using different math operations and the wiring paths is shown in Figure 3.7.

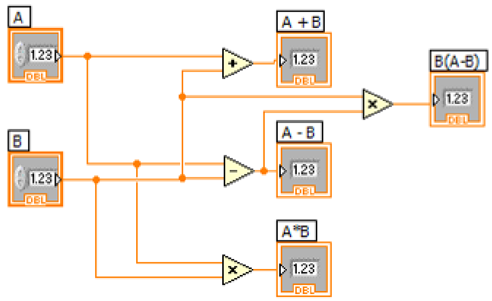


Figure 3.7 Mathematical operations

Express VIs

Express VIs are a recent addition to the LabVIEW software and are intended to accomplish common tasks such as data acquisition, analysis, writing to files, etc. Express VIs are functions that require minimal wiring because they are configured with dialog boxes. When placed in a block diagram, Express VIs appear as large elements with an icon surrounded with a light blue background. Double clicking on the element will return the user to interact with the configuration dialog box.

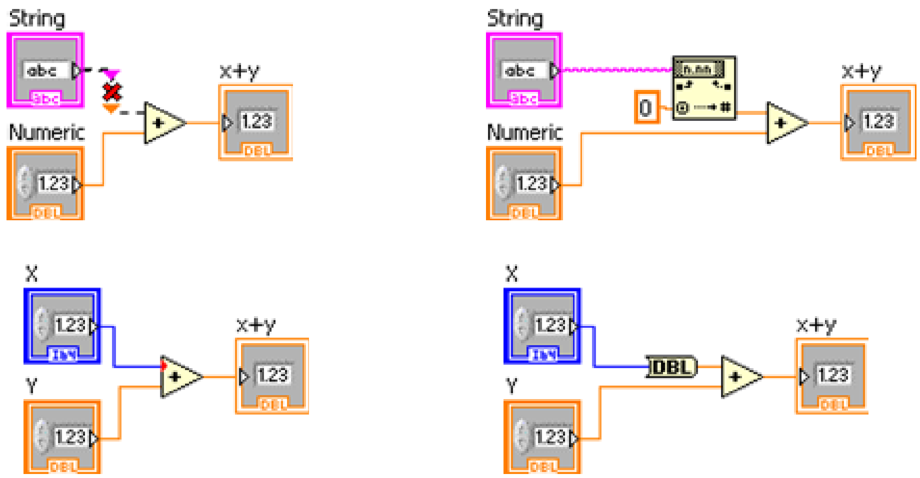
Data Types

Like other programming languages, LabVIEW works with different types of data. Wires and terminals are colored differently, depending on the data type being passed. Data types dictate what objects, inputs and outputs can be wired together. Table 3.1 presents the different data types and the wire colors representing the type.

Table 3.1 Data Types

Wire Color	Data Type Representation
Orange	Numeric (Floating Point)
Blue	Numeric (Integer)
Green	Boolean
Pink	Text String
Brown	Waveform
Navy Blue	Dynamic Data Type

Different data types can not be connected within a function. A broken wire, or a red warning dot, will appear as shown in Fig 3.8. However, the data can be converted, which is called "Type Casting".



(a) incorrect (b) converted

Figure 3.8 Converting data types

Dynamic data type (DDT) is associated with most Express VIs as shown in Fig. 3.9. This data type can carry different forms of information. However, some VIs do not accept DDT directly. Convert from DDT, and Convert to DDT functions are found on the Signal Manipulation palette.

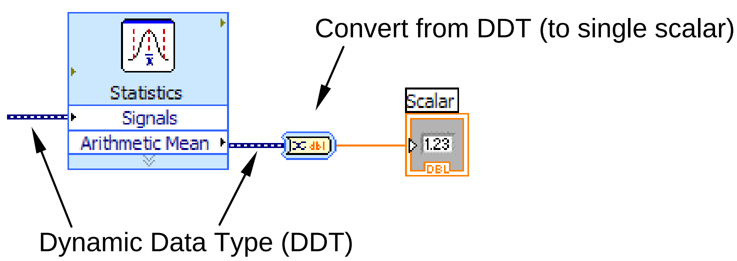
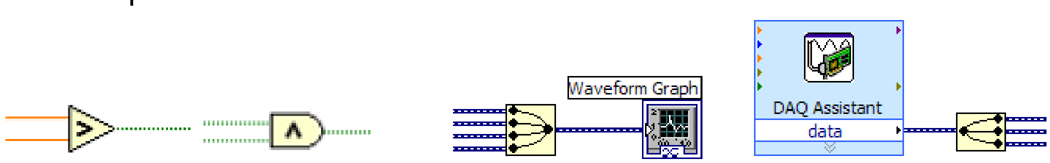


Figure 3.9 Dynamic Data Type.

Comparisons

Comparison functions are used to make decisions depending on data presented. Comparisons, as shown in Fig. 3.10a, accept numeric data and produce a Boolean output.



(a) (b) (c) (d)

Figure 3.10 Dynamic Data Type.

Logic
Logic functions are commonly used to make comparisons of Boolean data presented. The "and" function, or gate, shown in Fig. 3.10b, will output true data only if both inputs are true. Or and not gates are also commonly used functions.

Merge or Split Signals
Situations occur where it is desired to merged several signals into one DDT. Merge signal is a function available on the Signal Manipulation palette. The merge signal function is shown in Fig. 3.10c to combine several signals and plot them on the same graph. The merge signal function can be expanded to accommodate additional signals by dragging the element. A split signal function performs the opposite task. It divides off different signals that are present in a DDT. The split signal function is shown in Fig. 3.10d to break apart the different components of measurement signals through the Data Acquisition Express VI.

Signal Analysis
The most powerful functions used in data acquisition and measurement applications is located on signal analysis palette, as shown in Fig. 3.11.

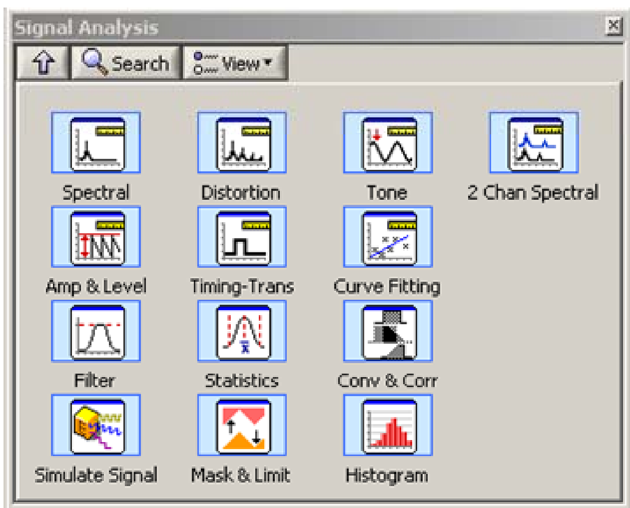


Figure 3.11 Signal Analysis Palette.

Arrays
An array is a variable sized collection of data elements. Arrays can be created and initialized as shown in Fig 3.12. Figure 3.12a shows a 1 dimensional array and Fig. 3.12b is a 2 dimensional array.

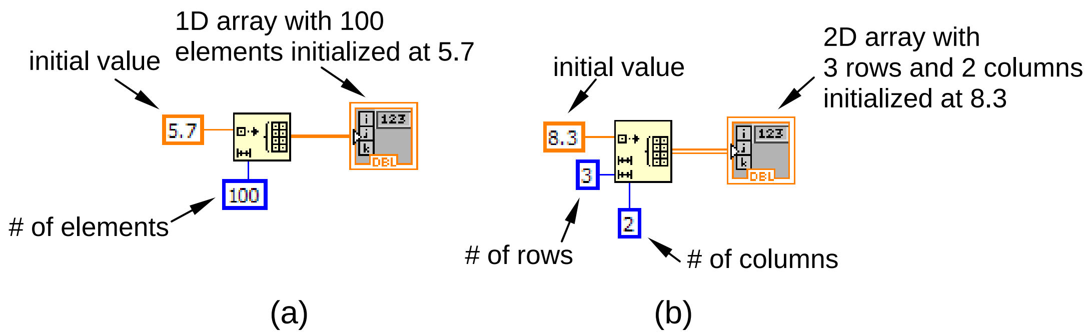


Figure 3.12 Signal Analysis Palette

Arrays can be built as shown in Fig. 3.13. Many built-in functions are able to manipulate arrays, such at the statistics function shown in Fig. 3.13 or the plot function shown in Fig. 3.14.

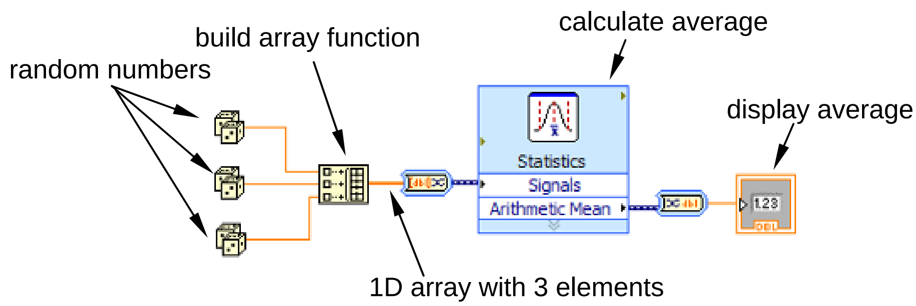


Figure 3.13 Build Array and Calculate Average

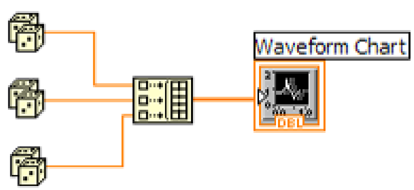


Figure 3.14 Build Array and Plot Elements

3.4 Structures

Structures manage the flow of data through a VI. Structures include a Loop, Case Structure and Flat Sequence. These items are located in the Functions palette, under the Execution Control icon.

Loops

Loops are used to perform repetitive operations. A For Loop executes until a specified number of iterations is completed. A While Loop executed until a specified condition is true.

The example shown in Figure 3.15 shows a while loop, seen as the bold grey frame. The conditional terminal is shown as a small stop sign is at the lower left corner of the loop. This terminal requires Boolean data, and terminates execution of the loop if that data is true. By right clicking on the border of the loop, the conditional terminal can be changed to stop is the conditional terminal input data is false.

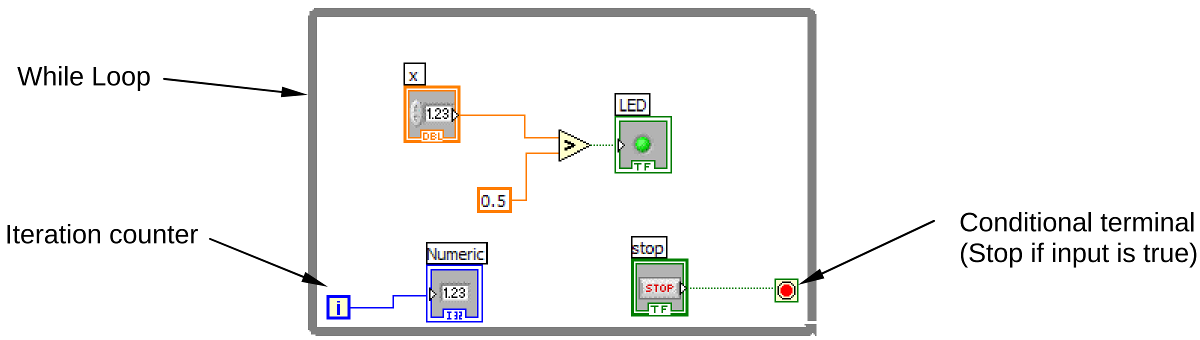


Figure 3.15 While loop.

Shift Registers

When using loops, data from the previous iteration is needed. A shift register transfers data from one iteration to the next. The shift register is comprised of a pair of terminals directly opposite to each other on the vertical sides of the loop border. A shift register is created by right clicking on the border of the loop and selecting "Add Shift Register". Figure 3.16 shows an example that uses a while loop with a shift register. The VI increases and displays an integer every second.

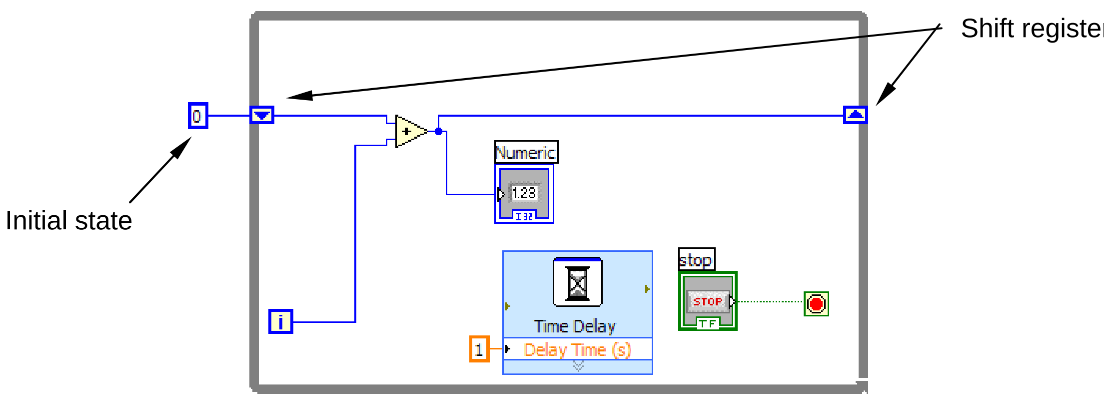


Figure 3.16 While loop with shift register.

Case Structures

A case structure is used to execute conditional text. This is similar to a common If…Then…Else statements in conventional text-based programming language. A case structure can have multiple subdiagrams that are configured like a deck of cards, were only one card is visible at a time. Different code is placed in each border associated with a case. Figure 3.17a shows a Boolean case structure. Figure 3.17b shows a numeric case structure. A selector label displays the value that cause the corresponding subdiaram to execute. A control is wired to a selector terminal, which dictates the selector setting, and the code to be executed.

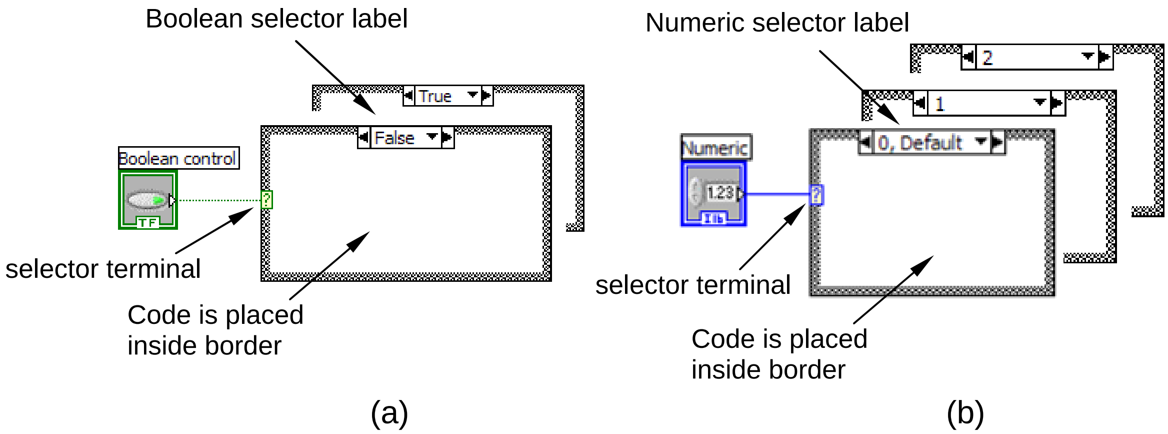


Figure 3.17 Case Structures.

A menu is displayed after right-clicking on the Case structure border. Through the menu, cases can be added, removed, and a default case can be assigned.

3.5 Data Acquisition

The most common usage of LabVIEW is to interact with external devices. Acquiring measurement data from sensors. The Data Acquisition (DAQ) Assistant is an express VI that leads the user through a series of that sets up a channel for measurement data to be read. Once configured the measurement data acquired can be processed, displayed, and written to a file using the many LabVIEW functions and operations. A simple VI to acquire a measurement and display it is shown in Fig. 3.18. Data acquisition is the focus of the following chapter.

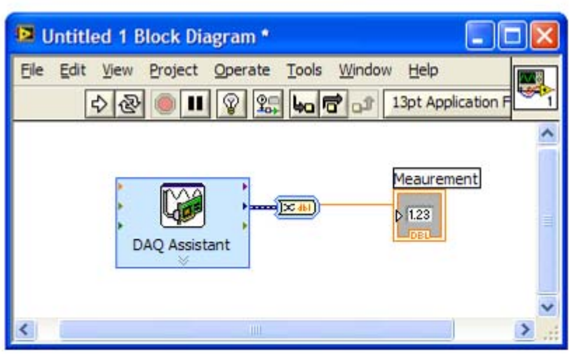
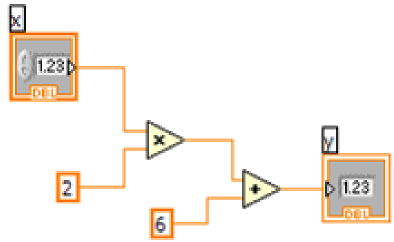


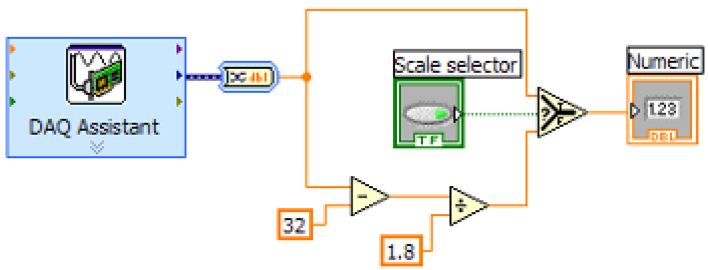
Figure 3.18 DAQ Assistant

Pre-Lab Exercises:

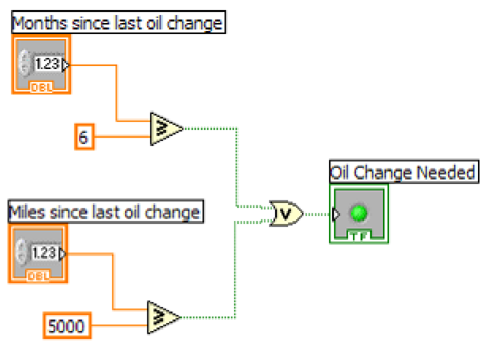
3-1. Describe the specific tasks completed in the following VI.



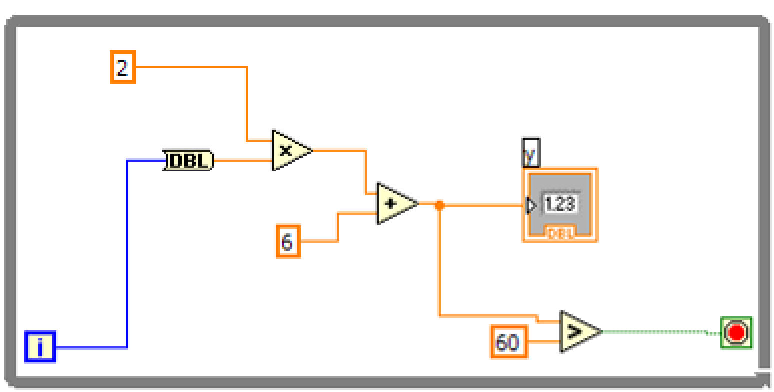
3-2. Describe the specific tasks completed in the following VI.



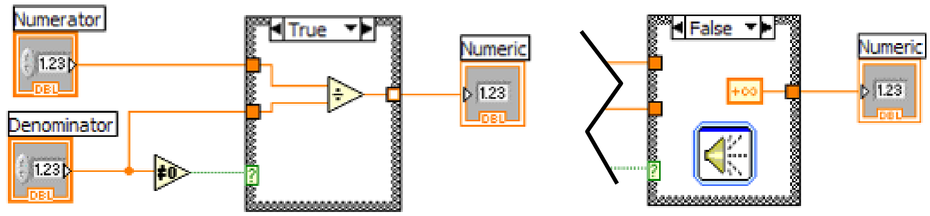
3-3. Describe the specific tasks completed in the following VI.



3-4. Describe the specific tasks completed in the following VI.



3-5. Describe the specific tasks completed in the following VI.



Laboratory Experiences:

3-1. Create a VI performs the following tasks:

a) Takes two floating point numbers as inputs on the front panel: *X* and *Y*.
b) Subtracts *Y* from *X* and displays the result on the front panel.
c) Divides *X* by *Y* and displays the result on the front panel.
d) If *Y* = 0, a front panel LED lights up to indicate division by zero.

3-2. Create a VI performs the following tasks:

a) Takes two floating point numbers as inputs on the front panes: *Side1*, *Side2* and *Angle3*.
b) Calculates the third side of a general triangle and displays the result on the front panel. As all computer programs, all trigonometric functions work with angles in radians.
c) Calculates the two remaining angles and displays the results on the front panel.
d) Writes all values to a file.

3-3. Create a VI performs the following tasks:

a) Uses a vertical slide control for input of a length value between 1 and 18 inches.
b) Converts the length into millimeters and numerically display that value on the front panel.
c) Writes both values to a file.
d) If the value is greater than 8 and less than 14, turn on an LED.

CHAPTER

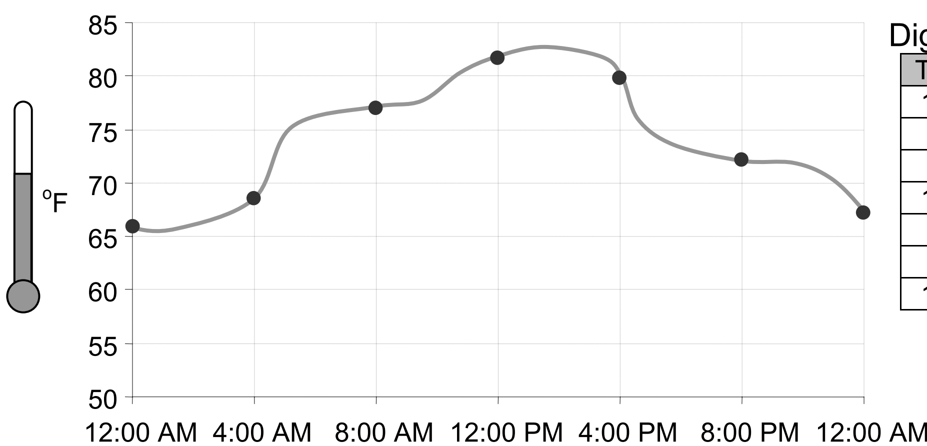
4

DATA ACQUISITION

4.1 Analog and Digital Signals

Most physical events that are to be measured involve continuously observable occurrences, called an analog form. An analog signal is one that varies with time in a smooth and uniform manner without discontinuities. A common example is an analog clock with an hour, minute and second hand that constantly sweep across the face.

Data acquisition captures discrete measurements of the continuous occurrence. The process of data acquisition captures individual readings associated with specific times from an analog signal. The analog event is converted into digital form. In contrast to an analog signal, a digital signal is a set of values where the identification of certain levels, or states, are permitted. A digital clock displays an hour and minute, then switches to the next minute. Figure 4.1 illustrates the actual temperature experienced throughout the day, represented by the curve. Readings are taken at four hour intervals, represented by the dark points. The set of points form the digital data signal.



Digital Signal:

Time	Temp.
12:00 AM	66 °F
4:00 AM	68 °F
8:00 AM	77 °F
12:00 PM	82 °F
4:00 PM	80 °F
4:00 PM	73 °F
12:00 PM	67 °F

Figure 4.1 Temperature measurements over one day

The quality of the data acquisition process will depend on how fast the physical event changes relative to the time interval of the recorded data points. The rate at which data is collected is called the sampling frequency, f_s. The quality the data acquisition process will also depend on the allowable levels of the digital values. The increment of change in a digital signal is called quantization size, Q.

4.2 Resolution and Quantization

A digital recorder, such as a computer data acquisition system is specified as an m-bit device. A bit is the smallest unit of information, being a single digit, either a 1 or a 0. By combining bits, it is possible to represent integers greater than a 1 or a 0. A word is an ordered sequence of bites with a byte being a specific sequence of 8 bits.

A combination of m-bits can be arranged to represent 2^m different words. For example, 2 bits can represent $2^2 = 4$ different combinations (00, 01, 10, 11). These combinations can be converted to represent a base 10 decimal number (0, 1, 2, 3). So, an 8-bit word can represent numbers 0 through 255. A 16-bit word can represent numbers 0 through 65,535.

Resolution is the number of bits of an analog-to-digital (A/D) converter. In the same manner as described above, the number of digital states, M, for a m-bit data acquisition system is

$$M = 2^m \qquad (4.1)$$

The analog range of an A/D converter is specified as a minimum and maximum voltage level. The limits of these values are set for a specific commercial converter. Often, lower limits can be specified, re-defining the operating voltage range of the converter. This will provide a better conversion accuracy, as will be discussed later. If either maximum or minimum limit is exceeded, the A/D converter output saturates and will not change with a subsequent increase in input level.

The A/D converter converts the an analog voltage into a binary number in a process called quantization. The quantization size, Q, is the amount of analog change that can be detected by the A/D converter. Alternatively, the quantization size represents the increment of change in the digitized measurement .

$$Q = \frac{(V_{max} - V_{min})}{M} = \frac{(V_{max} - V_{min})}{2^m} \qquad (4.2)$$

Figure 4.2 illustrates an analog signal and its digital representation. The quantization size is clearly identified. Also shown is saturation error, because the analog signal exceeded the maximum set converter voltage.

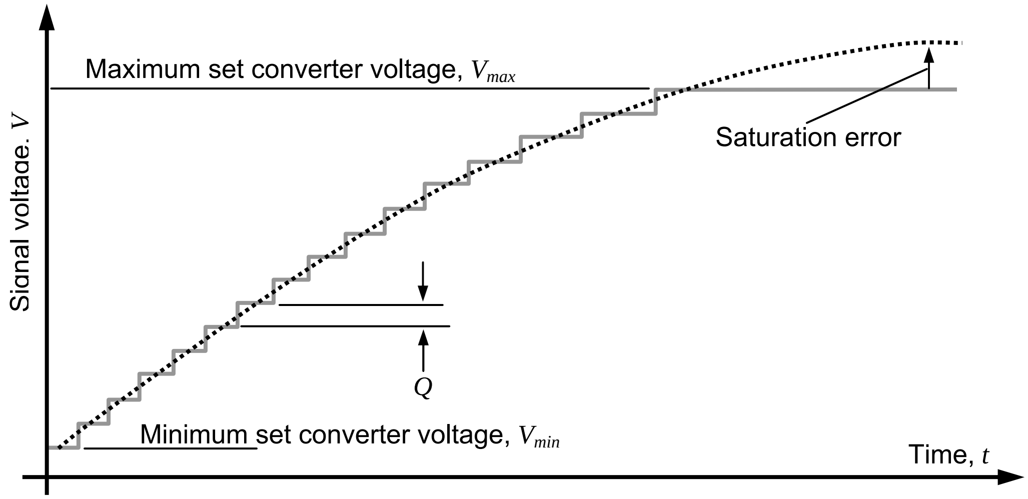


Figure 4.2 Analog-to-digital conversion

4.3 Sampling Rate

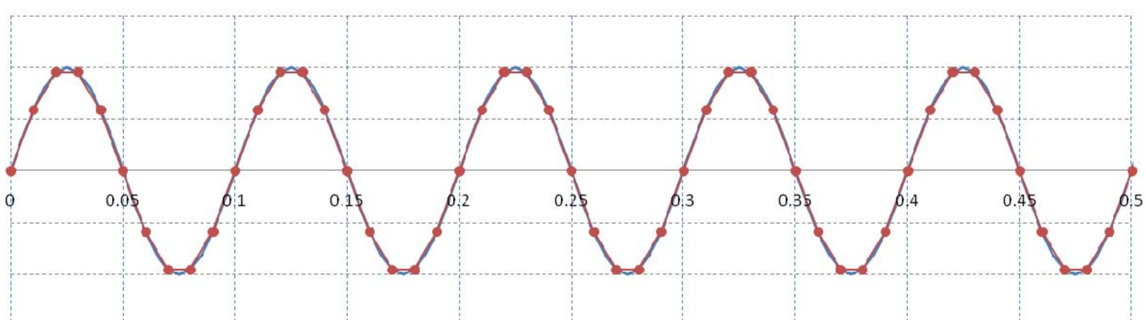
The sampling rate, or sampling frequency, f_s, is the speed at which data is acquired. The sampling frequency must be such that the analog signal is sufficiently captured by the series of data points. Clearly, the selection of the sampling frequency is dependant on how rapidly the measured signal changes.

The sample time increment, δt, is related to the sampling rate through

$$\delta t = 1/f_s \tag{4.3}$$

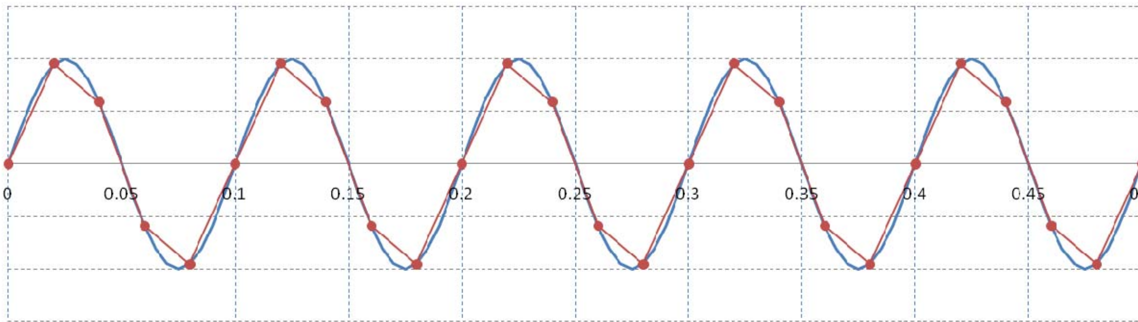
$$f_s = 1/\delta t \tag{4.4}$$

To understand the effect of acquisition rate on the accuracy of the digitized signal, Fig. 4.3 shows a analog signal and its digital representation. The measured signal is periodic with a constant frequency, f_m. In each case, the sampling rate is different. Notice that the representation quickly degrades as f_s<10 f_m. The frequency of the digital representation is incorrect when $f_s \leq 2 f_m$.



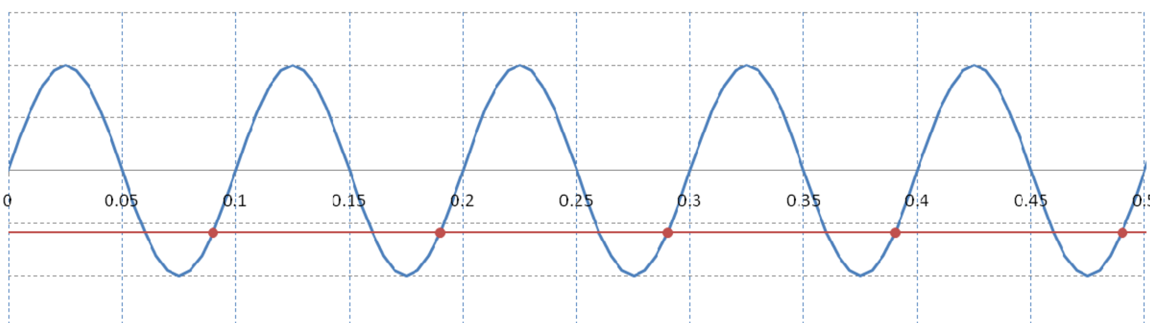
(a) A 10 hz signal from a sensor is acquired with a sampling rate of 100 hz

Figure 4.3 Effect of sampling rate on signal.



(b) A 10 hz signal from a sensor is acquired with a sampling rate of 50 hz

(c) A 10 hz signal from a sensor is acquired with a sampling rate of 25 hz



(d) A 10 hz signal from a sensor is acquired with a sampling rate of 20 hz

(e) A 10 hz signal from a sensor is acquired with a sampling rate of 10 hz

Figure 4.3 Effect of sampling rate on signal (con't)

The sampling theorem states that to obtain information about the frequency of a measured signal, f_m, the sampling rate, f_s, must be more than twice the highest frequency contained in the signal. This limit is designated as Nyquist criteria.

$$\text{Nyquist criteria:} \qquad f_s > 2\, f_m \qquad (4.5)$$

4.4 Commercial Systems

Many companies supply data acquisition equipment. Selection criteria should include:

Input Ranges
The voltage range that must be measuring is the primary selection issue. The range of output voltage should match that from which the sensors will provide. This results in the ADC utilizing the greatest number of data points in the range to be measured, thereby providing the highest possible resolution. Many boards provide adjustable input ranges by using software-programmable-gain amplifiers

Input Types
The number of input channels on data acquisition boards typically range from 4 to 64. Input channels can be single-ended (SE) or differential (DI), and many boards allow you to choose between the two types.

Accuracy
The major component of accuracy, and its limiting factor, is resolution.

Output Types
The number of output channels and the output current become important factors in control applications.

Speed
The throughput of a board, specified in kilosamples per second (kS/s). If multiple A/D converters are used on a single board, the specified throughput represents the sum total of the individual converter throughputs. For example, to sample four channels at 40 kS/s each, a throughput of at least 160 kS/s is required.

Most analog output circuits have a separate D/A converter and data buffer for each channel. The major portion of D/A throughput is the time needed to reach rated accuracy after receiving an output change.

Clocks, Triggers, Etc.
To perform multiple conversions at precisely defined time intervals, many data acquisition boards come equipped with one or more pacer clock circuits. Many boards also contain general purpose counter/ timer circuits. These consist of several counters and a frequency source.

The specifications for the National Instruments NI USB-6221 data acquisition board is given in Table 4.1.

Table 4.1 NI USB-6221 Specifications

Connection Type:	USB
Measurement Type:	Voltage, Quadrature encoder
Analog Input	
Number of Channels	16 single-ended inputs or 8 differential inputs
Sample Rate	250 kS/s
Resolution	16 bit
Maximum Voltage Range	-10 … 10 V
Minimum Voltage Range	-200 … 200 mV
Analog Output	
Number of Channels	2 differential outputs
Update Rate	833 kS/s
Resolution	16 bits
Maximum Voltage Range	-10 …10 V
Current Output	5 mA
Digital Input/Outputs	
Number of Channels	24
Maximum Clock Rate	1 MHz
Logic Levels	TTL
Voltage Range	0…5 V
Current output per channel	24 mA
Counters/Timers	
Number of Counter/Timers	2
Resolution	32 bits
Maximum Source Frequency	80 MHz
Minimum Input Pulse Width	12.5 ns
Logic Levels	TTL
Maximum Range	0..5 V
Timebase Stability	50 ppm
Pulse Generation	Yes
Timing/Triggering/Synchronization	
Triggering	Digital

4.5 Connector Block

A connector block is a interface that organizes the connections of the input and output signals with the data acquisition card. The physical connections can be made with screw terminals or BNC connectors. Figure 4.4 shows the connections on the National Instruments BNC-2120.

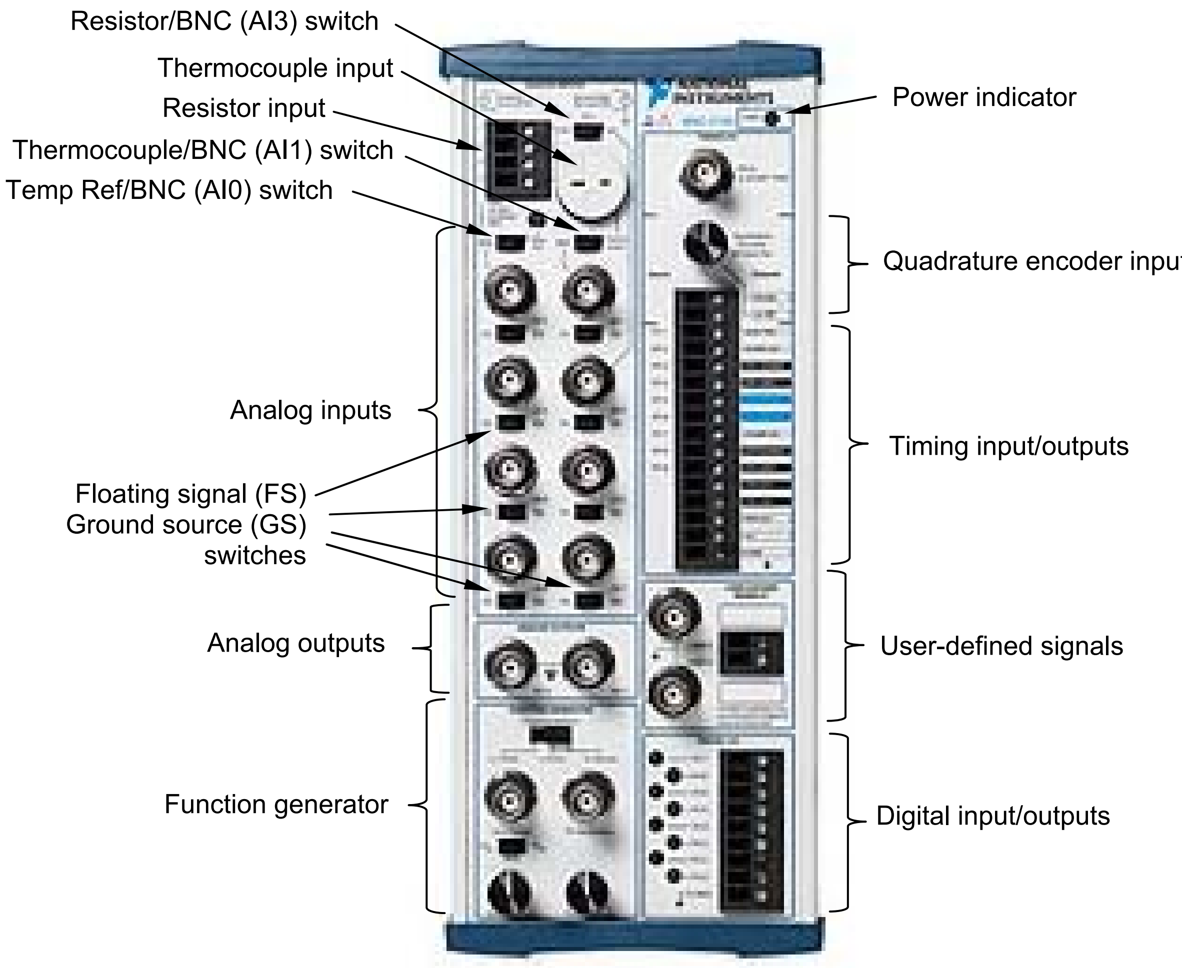


Figure 4.4 BNC-2120 Connector Block

4.6 Configuring a Channel with LabVIEW

LabVIEW has the DAQ Assistant Express VI that has a series of dialog boxes that configure a channel for acquiring data. The DAQ Assistant is placed onto the block diagram. Accessing the VI from the function palette is shown in Fig. 4.5.

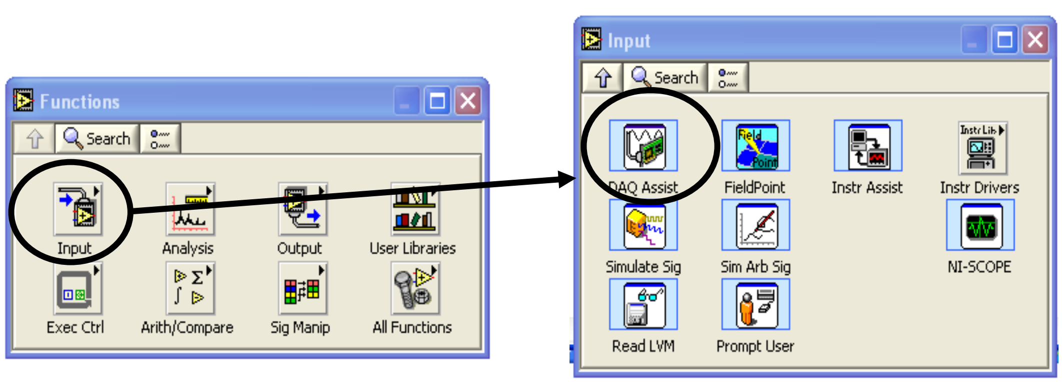


Figure 4.5 DAQ Assistant Express VI

The first dialog, shown in Fig. 4.6, identifies the type of signal to be processed.

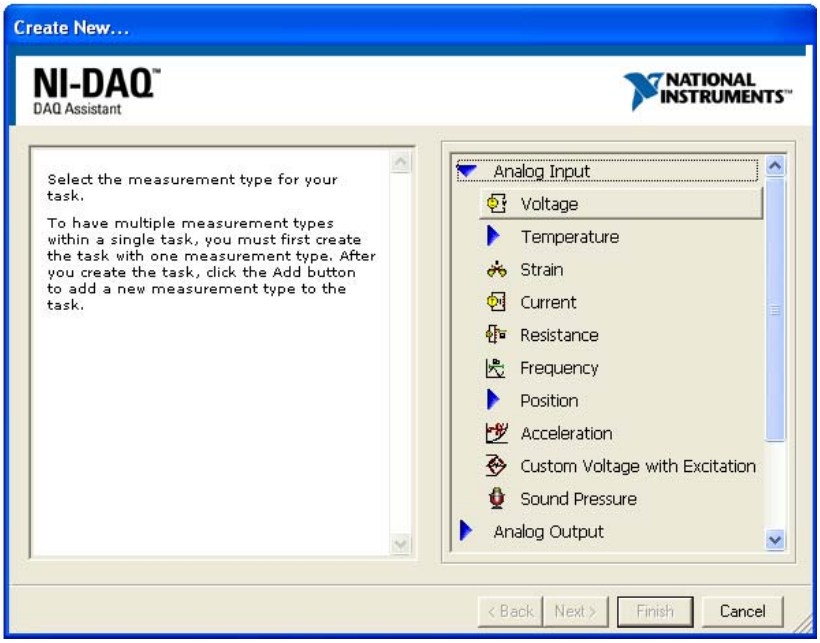


Figure 4.6 DAQ Assistant Measurement Type Dialog

The next dialog specifies the physical channel to be configured. The physical channel should correspond with the connection made on the connector block as shown in Fig. 4.7.

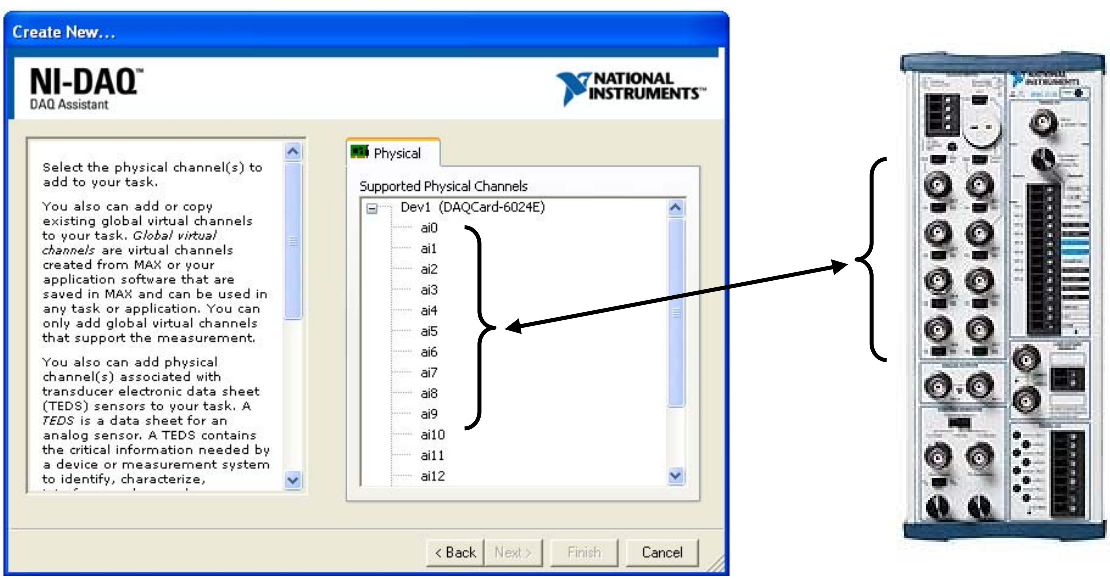


Figure 4.7 DAQ Assistant Physical Channel Dialog

The next dialog configures the channel, and is shown in Fig. 4.8. These extremely important settings include

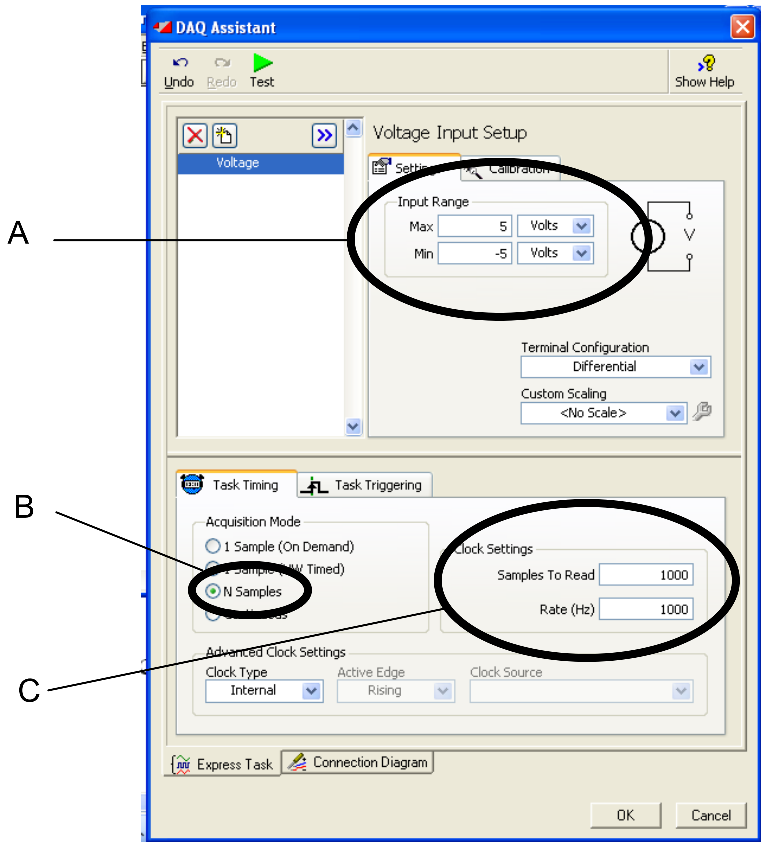


Figure 4.8 DAQ Assistant Configuration Dialog

The configuration settings are extremely important and include.

A. The maximum and minimum voltage input are entered into boxes the labeled A. To minimize quantization error, these should match the extreme values of the expected voltages of the acquired signal. These settings can be different for each channel being configured.

B. The type of acquisition mode is entered with the radio buttons labeled B. A single reading or a series of N readings can be acquired.

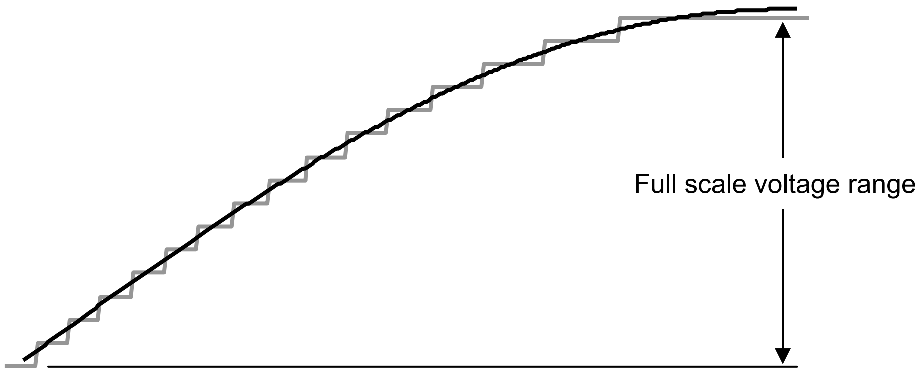
C. If N readings are selected, the number of points to acquire and the sampling rate, f_s, are entered into boxes the labeled C. The rate of change, or frequency, of the signal being acquired should be estimated to select an appropriate sampling rate. The number of points acquired, N, determine the length of the acquisition task, t_s.

$$t_s = \frac{N}{f_s} \qquad (4.6)$$

When several channels are being acquired, the task timing settings must be the same for all channels.

Pre-Lab Exercises:

4-1. The full range of an A/D converter was used to collect the following signal. Determine the size (number of bits) of that converter.



4-2. A channel on a 8-bit DAQ board is configured to read between +5.0 and -5.0 V. Determine the quantization size.

4-3. A channel on a 16-bit DAQ board is configured to read between +5.0 and -5.0 V. Determine the quantization size.

4-4. A DAQ channel is being configured to acquire 2000 points at 500 hz. Determine the length of the acquisition task.

4-5. A DAQ channel is being configured to acquire 200 points at 1000 hz. Determine the length of the acquisition task.

Laboratory Experiences:

4-1. Use computer data acquisition to determine the accuracy of the power supply display.

a) Connect the power supply to analog input channel 4 on the BNC 2120 breakout board.
b) Use a handheld multi-meter to measure the voltage from the power supply.
c) Use the computer DAQ to measure the voltage from the power supply.
d) Compare the power supply readings with the meter and DAQ by calculating:

- absolute error,

$$e = V_{P.S.} - V_{D.A.Q.}, \qquad e = V_{P.S.} - V_{meter},$$

$$e = V_{meter} - V_{D.A.Q.}$$

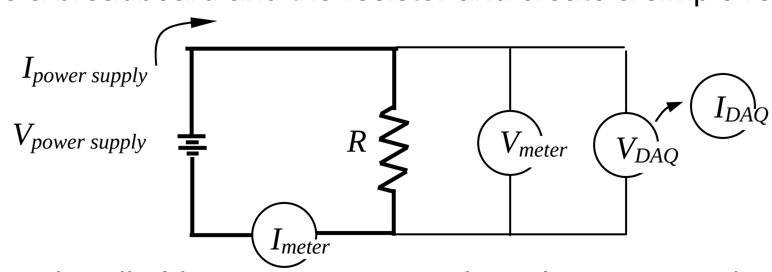
- percent error

$$\%e = 100\frac{\left(V_{P.S.} - V_{D.A.Q.}\right)}{V_{P.S.}}, \qquad \%e = 100\frac{\left(V_{P.S.} - V_{meter}\right)}{V_{P.S.}},$$

$$\%e = 100\frac{\left(V_{meter} - V_{D.A.Q.}\right)}{V_{P.S.}}$$

e) Repeat the measurements at several different voltages (at least 15).
f) Calculate the average, minimum, maximum, range, standard deviation.
g) Comment on the results and the trends.
h) Assuming a standard deviation, statistically determine:
   - The absolute error between the power supply and DAQ that will capture 95% of all readings.
   - The absolute error between the power supply and DAQ that will capture 99% of all readings.
   - The percent error between the power supply and DAQ that will capture 95% of all readings.
   - The percent error between the power supply and DAQ that will capture 99% of all readings.
i) As always, return equipment and clean-up the workstation.

4-2. Use computer data acquisition to determine the accuracy of the power supply current display.
a) Obtain a resistor (in the range of 300 – 800 Ω) and use the bench top multimeter to accurately measure its resistance.
b) Use a breadboard and the resistor and create a simple resistive circuit.



c) Use a handheld meter to measure the voltage across the resistor.
d) Configure the computer DAQ to measure the voltage from the power supply.
e) Using the measured resistance value, program LabVIEW to calculate the current through the resistor, and power dissipation.

$$I = \frac{V}{R} \qquad\qquad P = V\ I = I^2 R = \frac{V^2}{R}$$

f) Compare the power supply amperage with the meter amperage and the current calculated through DAQ by calculating:
   - absolute error,

     $$e = I_{P.S.} - I_{D.A.Q.}, \qquad e = I_{P.S.} - I_{meter},$$

     $$e = I_{meter} - I_{D.A.Q.}$$

   - percent error

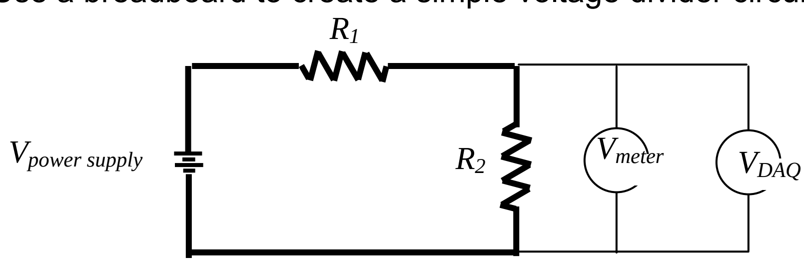
$$\%e = 100\frac{(I_{P.S.} - I_{D.A.Q.})}{I_{P.S.}}, \qquad \%e = 100\frac{(I_{P.S.} - I_{meter})}{I_{P.S.}},$$

$$\%e = 100\frac{(I_{meter} - I_{D.A.Q.})}{I_{meter.}}$$

g) Repeat the measurements at several different voltages (at least 10), and resistors (at least 3). Be cautious, as these are 0.125 watt resistors.
h) Comment on the results and the trends.
i) As always, return equipment and clean-up the workstation.

4-3. Use computer data acquisition to assess the performance of 16-bit, analog to digital conversion.

a) Obtain two resistors, $R_1/R_2 \approx 10$, and precisely measure their resistance.
b) Use a breadboard to create a simple voltage divider circuit.



c) Use a handheld multimeter to measure the voltage across the second resistor.
d) Configure the computer DAQ to measure the voltage from the power supply, and the voltage across the second resistor. Display both a single point reading, and the averaged reading. Keep the full scale voltage range of ± 10V.
e) Use LabVIEW to calculate use the power supply voltage to determine the expected voltage across the second resistor

$$V_{R_2} = \frac{R_2}{R_1 + R_2} V_{\text{power supply}}$$

f) Compare the expected voltage across the second resistor with the single point DAQ measurement, averaged DAQ measurement, and the multimeter.
g) Repeat the measurements at different supply voltages (about 6), up to 10 V.
h) Change the resistor ratio (R_1/R_2) to approximately 100, 500 then 1000 and repeat steps 6 and 7.
i) Comment on the results and the trends.
j) Suggest what can be done to minimize error in future testing.
k) As always, return equipment and clean-up the workstation.

CHAPTER

5

SIGNAL CONDITIONING AND PROCESSING

5.1 Noise and Interference

All acquired measurement signals are subjected to noise and interference. These factors corrupt a measurement and reduces accuracy.

Noise
Noise is a random variation of the measured signal as a consequence of the factors that are not controlled during testing. An example is changes in temperature of an oil while testing the flow capabilities of a pump. Since viscosity is strongly dependent on temperature, and the pumping action is dependant on viscosity, inherent variations will occur.

Noise increases data scatter. As presented in Chapter 1, the standard deviation is a measure of spread in a data distribution, these random variations can be characterized by the standard deviation of the measured signal. That is, the larger the standard deviation, the noisier is the measurement. A dc signal affected by noise is shown in Fig 5.1.

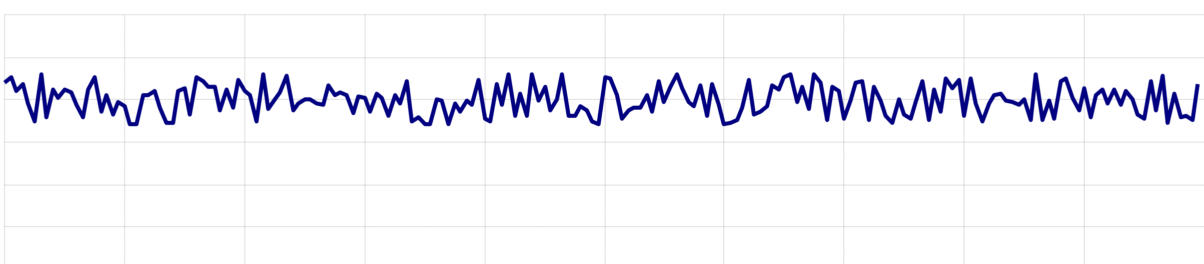


Figure 5.1 Actual Acquired DC Signal

The noise level of a signal is characterized by the signal to noise ratio (SNR). Since SNR is defined in terms of power, it is computed as the square the amplitude of the signal, V_S , divided by the square of the amplitude of the noise, V_N. The amplitudes are typically taken as root-mean-square values.

$$SNR = \frac{V_S^{\ 2}}{V_N^{\ 2}} \qquad (5.1)$$

In general, signals have a very wide dynamic range. Therefore, SNR is usually expressed in terms of the logarithmic decibel scale. In decibels, the SNR is

$$SNR(dB) = 20\log\left(\frac{V_S}{V_N}\right) \tag{5.2}$$

For a steady signal, the signal amplitude is the mean voltage value, $\bar{V}$. The noise is the square of the signal standard deviation, s. Thus, for a steady signal

$$SNR(dB) = 20\log\left(\frac{\bar{V}}{s^2}\right) \tag{5.3}$$

Interference
Interference is a deterministic effect that alters, modifies, or disrupts a signal as it travels between a source and a receiver. Hum and feedback in a public address system is a is an example of interference. The most common form of interference comes from an ac power source and is seen as a sinusoidal wave superimposed on the measurement. The result is the addition of unwanted signals to a useful signal.

Sometimes the interference in a measurement signal is obvious and can be readily removed. However, if the period of the interference is longer than the measurement made, a false trend will be observed.

The procedure of reducing or attenuating the noise and interference components of a measured signal is commonly known as filtering.

5.2 Signal Conditioning

Signal conditioning refers to the process of amplifying and filtering an analog measurement signal prior to data acquisition. The purpose of signal conditioning is to reduce the effect of noise and interference. Figure 5.2 shows the schematic of a generalized measurement system as presented in Chapter 1. Note that signal conditioning is a fundamental element in the system.

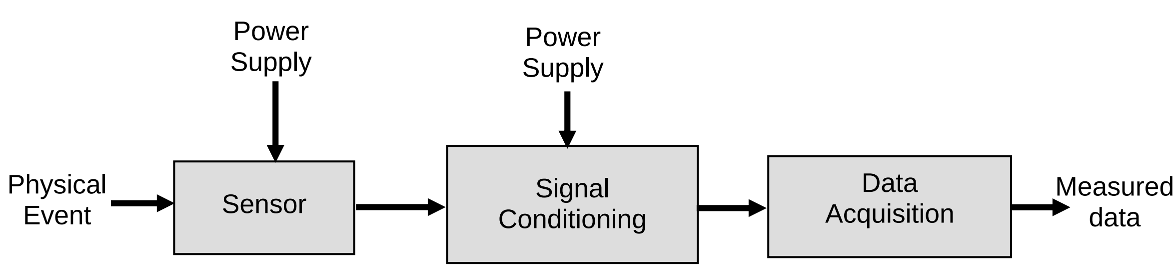


Figure 5.2 Generalized measurement system

The output from several common sensors is typically a low voltage, and noisy signal. Figure 5.3 illustrates a force transducer, which is a sensor that converts a force to a voltage. A large steady voltage (3 - 10V) is applied to the red and black wires. A small and noisy signal (0.003 – 0.030 V) which is proportional the force applied is witnessed across the green and white wires. To increase the accuracy of the measurement, this signal should be conditioned.

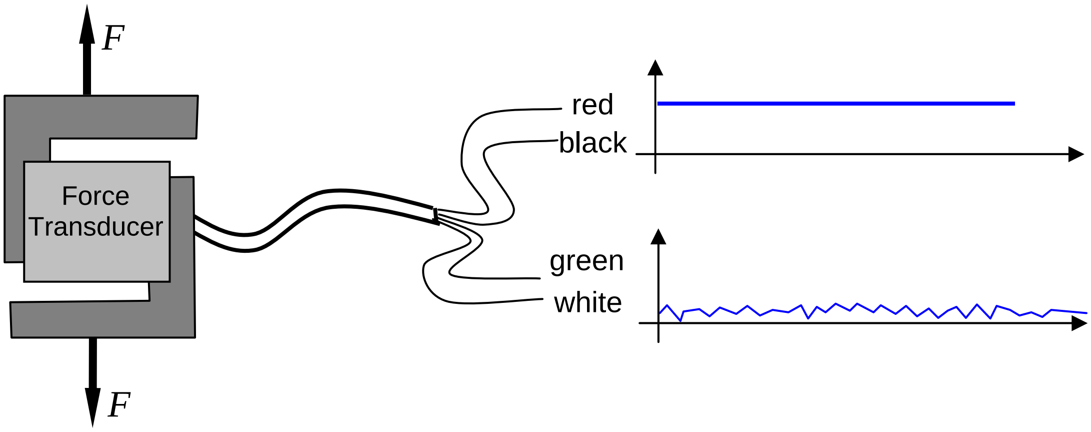


Figure 5.3 Force Transducer

Signal conditioners use operational amplifiers, as presented in Chapter 2, to amplify a signal. Low pass filters are used to eliminate high frequency interference and noise. A simple board that has been constructed that contains an instrumentation operational amplifier and a low pass filter is shown in Fig 5.4

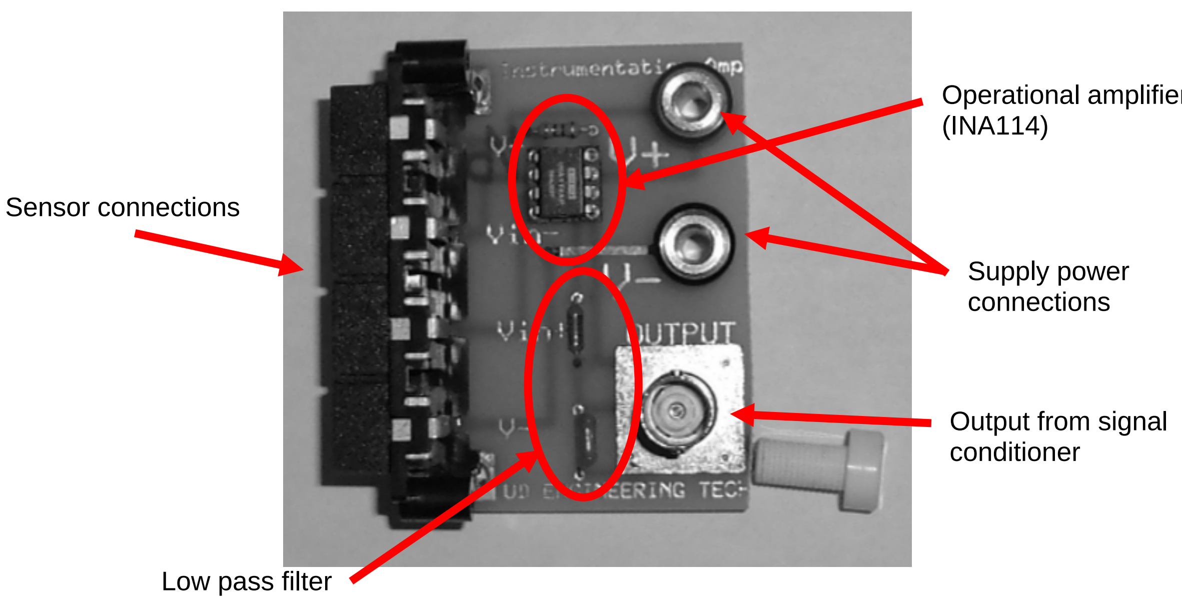


Figure 5.4 Signal Conditioner

Commercial signal conditioners have internal power supplies, adjustable balance and gain, and adjustable cut-off frequency for the low pass filter. The Vishay 2210 signal conditioner is shown in Fig 5.5.

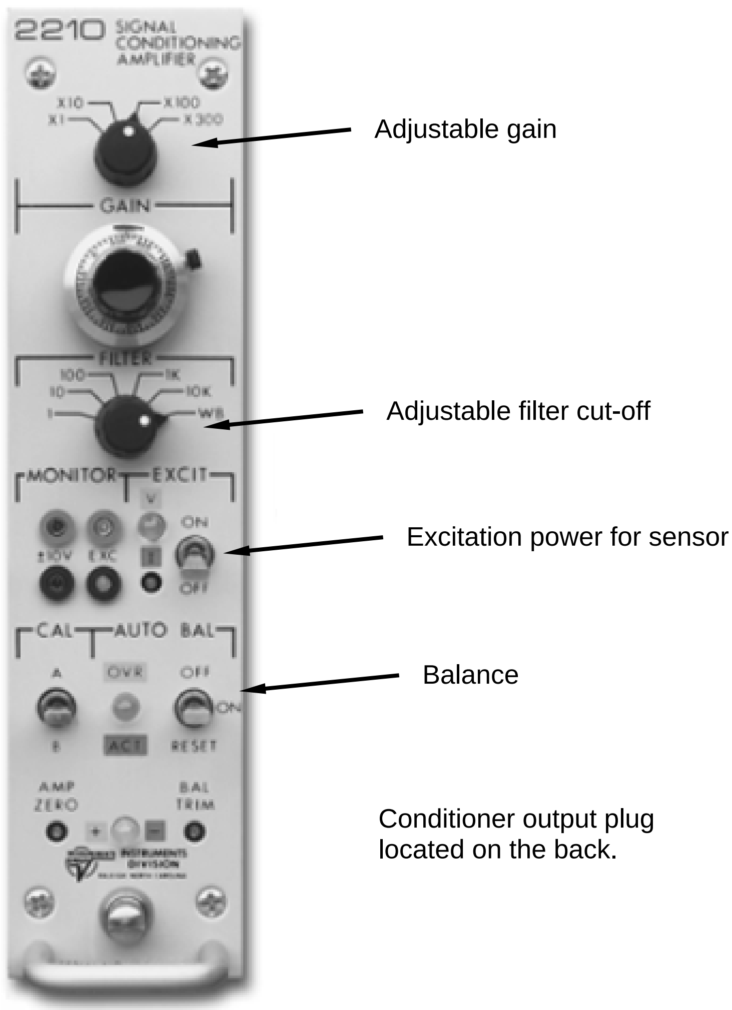


Figure 5.5 Vishay 2210 Signal Conditioner

5.3 Smoothing Filters

Once a signal is acquired, it can be further processed to further eliminate the effects of noise and interference. Some common forms of signal processing are described below.

Average
For static measurements, the acquired data points, x_i, can be averaged to eliminate all noise.

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad (5.4)$$

where N is the number of samples in the waveform.

Root-Mean-Square

The root-mean-square (rms) is used when the acquired signal contains no dc component, but the magnitude of a varying quantity is desired. The rms value of acquired data points, x_i, can be calculated as

$$x_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^{\ 2}} \qquad (5.5)$$

Moving Average

For dynamic measurements, a “chunk” of a waveform can be averaged to smooth out short term fluctuations. A series of averages are calculated from different subsets of the full data set. The width of the moving average, n, defines the number of points that are averaged. A central moving average is calculated as

$$\overline{x}_{j+n/2} = \frac{1}{n}\sum_{i=j}^{j+n-1} x_i \qquad (5.6)$$

The effect of a moving average on an acquired signal is shown in Fig 5.6. Clearly the effects of high frequency noise and interference is reduced.

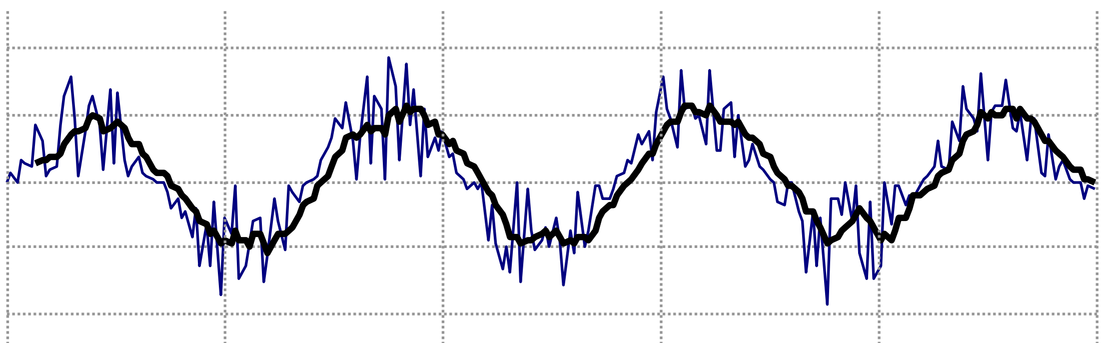


Figure 5.6 Effect of a Moving Average on a Measurement Signal

Low Pass Software Filter

Similar to a hardware low pass filter, the software filter numerically eliminates the components of a signal that have frequencies above a designated cut-off. The is represented by the plot shown in Fig 5.7. The numerical method that accomplishes a software based low pass filter uses Fourier analysis which is presented in the next section.

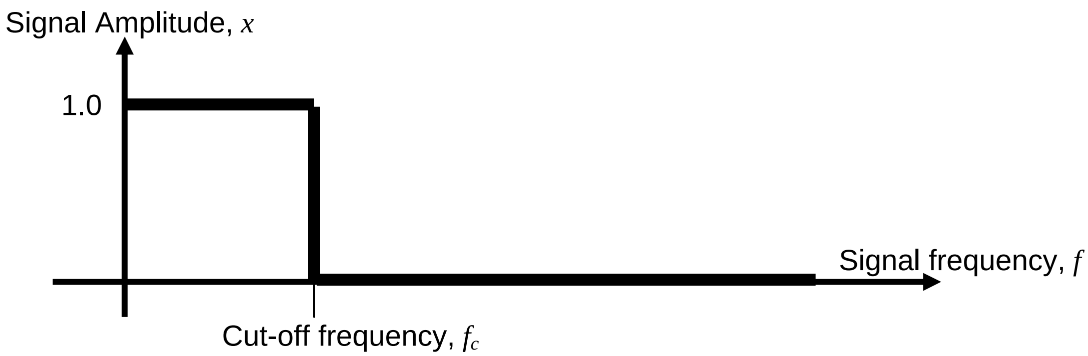


Figure 5.7 Low Pass Filter

5.4 Fourier Analysis

A general dynamic signal as shown in Fig. 5.8 has an offset and harmonics, each with a distinct set of frequencies, amplitudes and phase angles. A general signal can be represented by a Fourier series:

$$x(t) = x_0 + \sum_{k=0}^{\infty} x_k \sin(2\pi\ f_k t + \phi_k) \qquad (5.7)$$

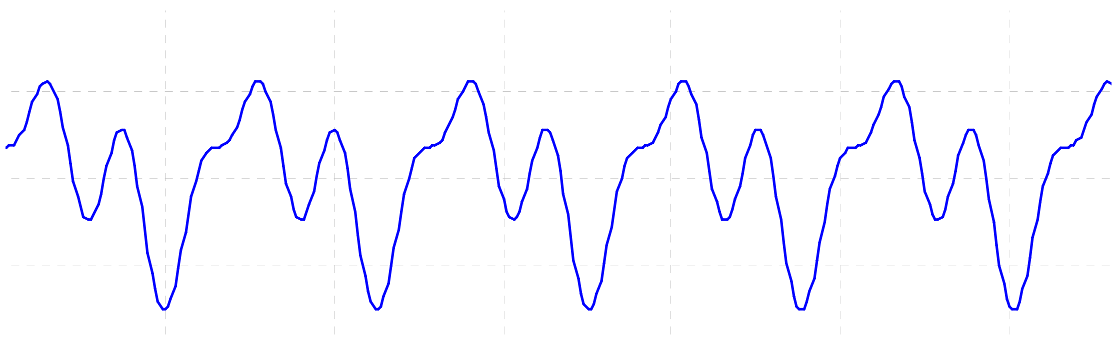


Figure 5.8 General Dynamic Signal

A Fast Fourier Transform (FFT) is a routine that dissects a general signal and determines the offset (x_0), amplitudes (x_1, x_2, x_3, …), frequencies (f_1, f_2, f_3, …), and phase angles (ϕ_1, ϕ_2, ϕ_3, …) that comprise the signal.

FFT is also classified as harmonic, or spectral, analysis. The results of the analysis are commonly given in graphical form, plotting magnitude versus frequency, or phase angle versus frequency. The magnitude can appear as either a linear or decibel scale. An example of a linear magnitude plot is shown in Fig 5.9

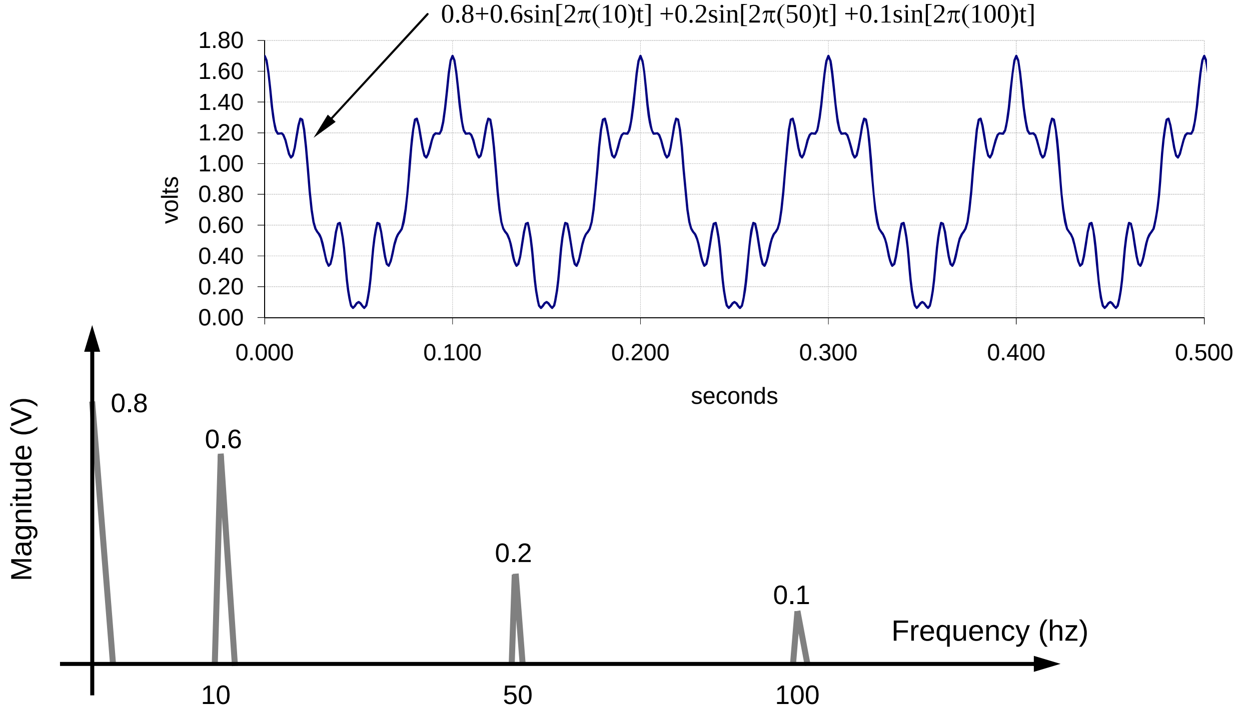


Figure 5.9 Example Fast Fourier Transform

Pre-Lab Exercises:

5-1. Use LabVIEW to:

a) Create three simulated signals with:

Signal	1	2	3
Frequency	40 hz	100 hz	600 hz
Amplitude (p-p)	1.0V	0.25V	0.1V
Offset	.25 V	0	0

b) Set timing (simulate data acquisition) to 250 samples at 5000 hz.

c) Add the three signals together

d) Plot the raw signal

e) Plot the signal after passing through a smoothing filter (moving average) with the half width ($n/2$) of 3.

f) Note the differences

g) Change the half-width and reevaluate.

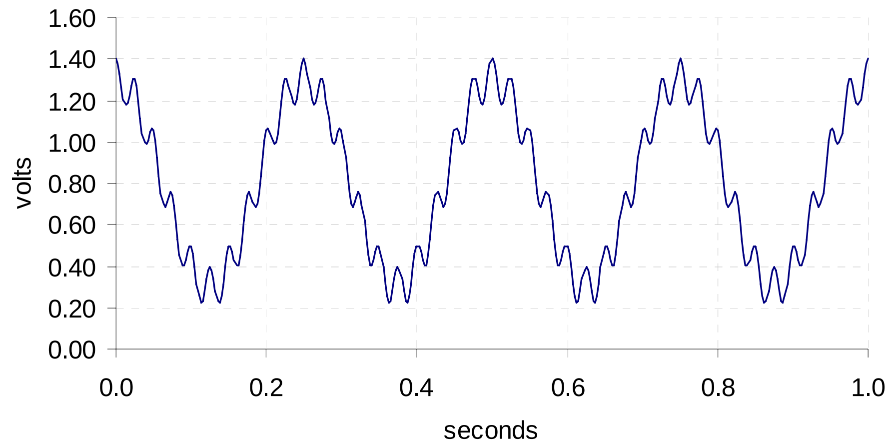
5-2. Use LabVIEW to:

a) Create three simulated signals with:

Signal	1	2	3
Frequency	40 hz	100 hz	600 hz
Amplitude (p-p)	1.0V	0.25V	0.1V
Offset	.25 V	0	0

b) Set timing (simulate data acquisition) to 250 samples at 5000 hz.
c) Add the three signals together
d) Plot the raw signal
e) Plot the signal after passing through a low pass filter (f_c = 500). Note the differences
f) Change the cut-off frequency and reevaluate.

5-3. Visually examine the following signal, and perform a Fourier analysis to solve for the frequency and amplitude components.



5-4. Use LabVIEW to:
a) Create three simulated signals with:

Signal	1	2	3
Frequency	40 hz	100 hz	600 hz
Amplitude (p-p)	1.0V	0.25V	0.1V
Offset	.25 V	0	0

b) Set timing (simulate data acquisition) to 250 samples at 5000 hz.
c) Add the three signals together
d) Plot the raw signal
e) Send the raw signal through a harmonic analysis (FFT) function and plot the results.

5-5. Use LabVIEW to:
a) Create three simulated signals with:

Signal	1	2	3
Frequency	40 hz	100 hz	600 hz
Amplitude (p-p)	1.0V	0.25V	0.1V
Offset	.25 V	0	0

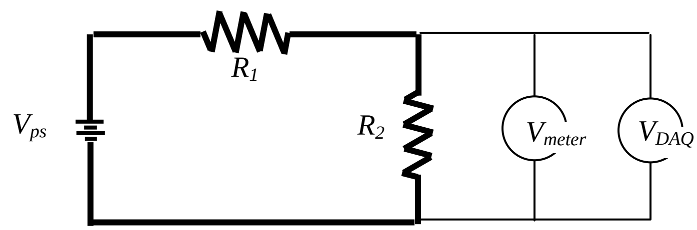
b) Set timing (simulate data acquisition) to 250 samples at 5000 hz.
c) Add the three signals together
d) Plot the raw signal
e) Pass the signal through a low pass filter (f_c = 500).

f) Pass the filtered signal through a harmonic analysis (FFT) function and plot the results.
g) Change the cut-off frequency and reevaluate the FFT plot.

Laboratory Experiences:

5-1. Determine the effectiveness of a signal conditioner.

a) Obtain two resistors, $R_1/R_2 \approx 250$, and precisely measure their resistance. Use a breadboard to create a simple voltage divider circuit.



b) Use a multimeter to measure the voltage across the second resistor.
c) Configure the computer DAQ to measure the voltage across the second resistor.
d) Make the power connections to the instrumentation amplifier
e) Connect the voltage across the second resistor to your instrumentation amplifier.
f) Connect the output of the instrumentation amplifier to the second channel of the LabVIEW.
g) Use LabVIEW to determine the signal to noise ratio before and after signal conditioning.
h) Determine the gain of the amplifier and the effectiveness of your amplifier & filter.
i) Repeat at different power supply voltages, V_{ps}.
j) Comment on trends that are observed.
k) As always, return equipment and clean-up workstation

5-2. Determine the effect of using software filters and harmonic analysis.

a) Route a 100 hz, 1.0 Vp-p, square wave signal from the function generator (50Ω connector) to any channel on the DAQ board.
b) Create a LabVIEW program to accept the signal. Select an acquisition rate such that 20 points per period are acquired, and capture 1 second of data.
c) Plot this “raw” signal on a waveform chart.
d) Send the signal into a low pass filter, with a 500 hz cutoff.
e) Plot the filtered signal on a waveform chart.
f) Perform an FFT (peak amplitude and linear scale) on both the raw and filtered signal and place on two separate charts.
g) Make a screen capture of the charts and comment on the plots. Compare and contrast them and the differences.

h) Change the cut-off frequency, to 300 hz, 150 hz, and 75 hz and repeat your analysis (step g).
i) As always, return equipment and clean-up workstation.

Chapter

6

DISPLACEMENT MEASUREMENTS

6.1 Position and Displacement

The position of an object is its absolute location (x, y, z), relative to a reference frame. However, a position measurement usually refers to the distance, s, between a reference point and the object whose location is being measured, often called the target.

$$s = \sqrt{x^2 + y^2 + z^2} \qquad (6.1)$$

Displacement, Δs, is the change of an object's position over a specified interval.

$$\Delta s = s_2 - s_1 = \sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2} \qquad (6.2)$$

A displacement measurement is the distance between the location of a target, and a previous location of a target. Displacement measurements are often used as sensors to provide feedback for devices in many automation applications such as gantry robots and CNC milling machines.

In summary, position refers to a measurement with respect to a constant reference datum. Displacement is a relative measurement.

Similarly, angular position, θ, and angular displacement, $\Delta\theta$, are defined and their measurements are also desired. Since angular measurements are typically easier to make, linear measurements are often accomplished with an angular sensor coupled to a mechanical mechanism that changes the linear displacement into angular displacement.

6.2 Measuring Linear Displacement

Linear displacement can be measured using the following sensors.

Linear Variable Resistance Transducer:
One of the simplest sensors for measuring displacement is a variable resistor similar to the volume control on a stereo. The resistance between two terminals on the variable resistor is related to the linear displacement of a sliding pick-up along a resistance element. These variable resistors are also called potentiometers and schematically shown in Fig. 6.1. Precision potentiometers are available that have a reproducible, linear relationship between resistance and displacement.

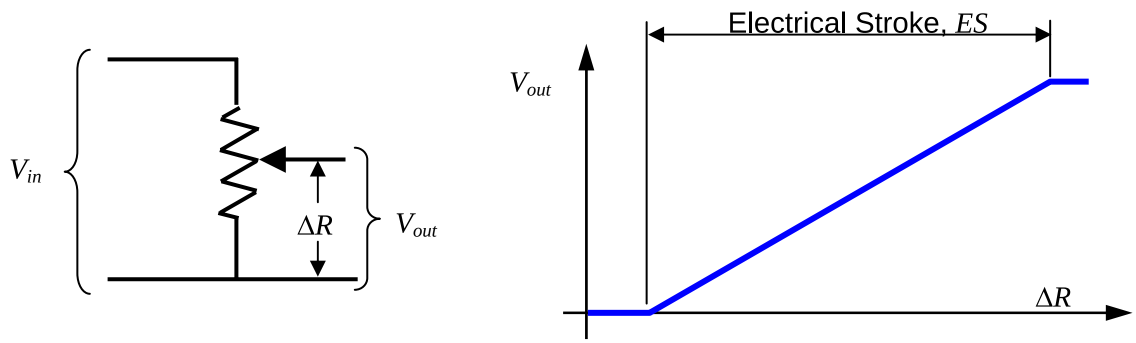


Figure 6.1 Variable Resistor (potentiometer)

A linear variable resistance transducer (LVRT) is a potentiometer configured to convert the linear motion of an object to which it is coupled mechanically into a proportional voltage. The coil of wire, with a slide that drags across the coilsA LVRT is shown in Fig 6.2.

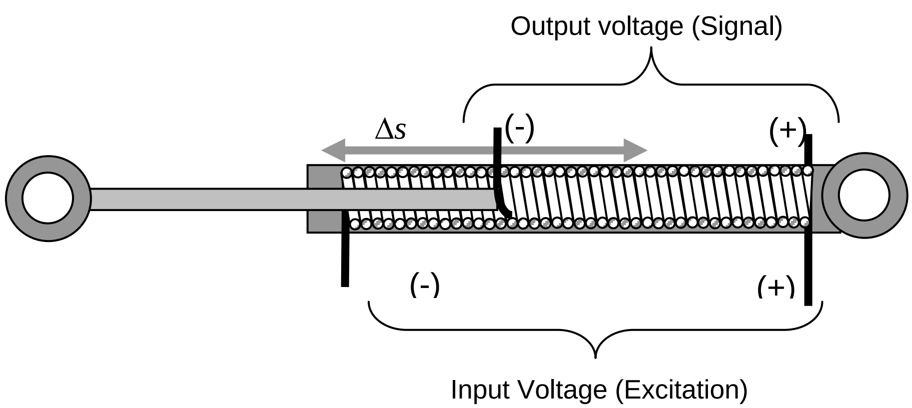


Figure 6.2 Linear Variable Resistance Transducer (LVRT)

An LVRT is classified by its stroke and resistance. The resistance is selected to achieve the desired current through the circuit. The mechanical stroke is the displacement range between the hard stops. The electrical stroke, ES, is slightly less and defines the distance between the positions where the signal begins to change, and where it stops changing, as shown in the plot of Fig. 6.1.

The displacement measured from the LVRT is determined from a linear relationship of the signal voltage.

$$\Delta s = ES\left(\frac{V_{signal}}{V_{excitation}}\right) \qquad (6.1)$$

While the LVRT provides absolute position and has simple electronics, there are some drawbacks. Significant current will introduce nonlinearities in the voltage vs. displacement characteristics. Additionally, the sensor has a physical sliding contact, which produces friction and limits the speed and life of the sensor.

Linear Variable Differential Transducer:

A linear variable differential transformer (LVDT) is another type of electromechanical transducer that converts linear motion into a corresponding electrical signal. The LVDT uses a electrical transformer to measure linear displacement. The transformer has three sets of coils placed end-to-end around a tube. The center coil is the primary, and the two outer coils are secondary. A iron core, attached to the object whose position is to be measured, slides along the axis of the tube.

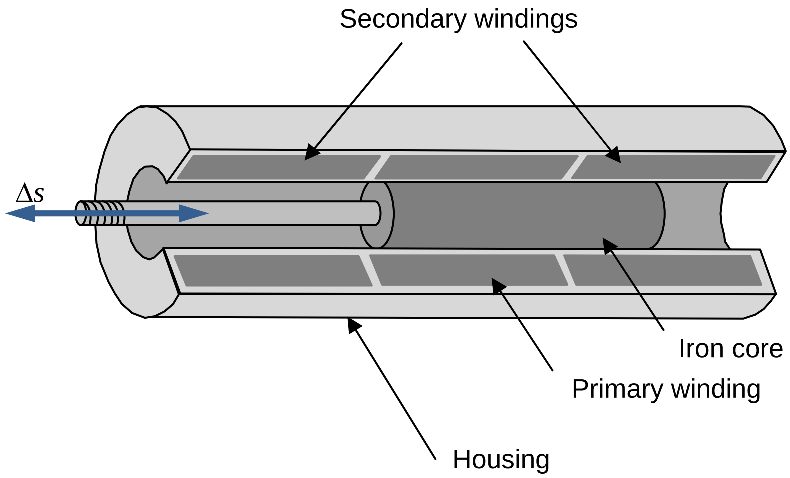


Figure 6.3 Linear Variable Differential Transducer (LVDT)

An alternating current is driven through the primary coil, causing a voltage to be induced in each secondary proportional to its mutual inductance with the primary. As the core moves, these mutual inductances change, causing the voltages induced in the secondary coils to change. The coils are connected in reverse series, so that the output voltage is the difference between the two secondary voltages. When the core is in its central position, equidistant between the two secondary coils, equal but opposite voltages are induced in these two coils, so the output voltage is zero.

When the core is displaced in one direction, the voltage in one coil increases as the other decreases, causing the output voltage to increase from zero to a maximum. This voltage is in phase with the primary voltage. When the core moves in the other direction, the output voltage also increases from zero to a maximum, but its phase is opposite to that of the primary. The magnitude of the output voltage is proportional to the distance moved by the core (up to its limit of travel), which is why the device is described as "linear". The phase of the voltage indicates the direction of the displacement.

Because the sliding core does not touch the inside of the tube, it can move without friction, making the LVDT a highly reliable device. The absence of any sliding or rotating contacts allows the LVDT to be completely sealed against the environment.

Linear encoder
A linear encoder is a sensor, which is comprised of a readhead sensor paired with a scale that with regularly spaced indicator marks. The readhead is attached to the object being measured. The scale is attached to a stationary reference. As the object moves, the sensor reads the scale marks, which can be decoded to determine the position of the object. A linear encoder is schematically shown in Fig. 6.4.

Figure 6.4 Linear Encoder

Most commercially available linear encoders are optical. Optical encoders measure the linear position of an object by detecting marks on a scale. Incremental encoders simply detect the relative motion of the object, rather than its absolute position by counting these marks. Although absolute linear optical encoders are available, they do not offer very high resolution.

Motion can be determined by change in position over time. Linear encoder technologies include capacitive, inductive, eddy current, magnetic, and optical.

6.3 Measuring Angular Displacement

Angular displacement can be measured using the following sensors.

Potentiometer:
As with linear measurements, the simplest sensor is a variable resistance transducer. Potentiometers configured in a rotary form can be a single turn, or multiple turns. The resistor in multiple turns potentiometer is arranged in a helical structure.

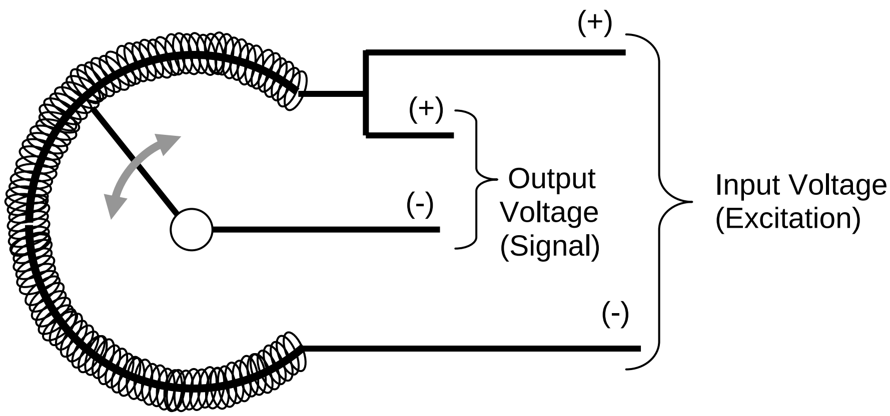


Figure 6.5 Rotary Potentiometer

As with the LVRT, the rotary potentiometer is classified by its stroke and resistance. The mechanical stroke is the angular range between the hard stops. The electrical stroke, ES_{θ}, is slightly less and defines the angle between the positions where the signal begins to change. The angle measured from the rotary potentiometer is determined from a linear relationship of the signal voltage.

$$\Delta\theta = ES_{\theta}\left(\frac{V_{signal}}{V_{excitation}}\right) \tag{6.2}$$

Rotary encoder

Like its linear counterpart, a rotary encoder is a sensor, which is comprised of a readhead sensor paired with a disk that with regularly spaced indicator marks. The disk is attached to the shaft being measured. The readhead is attached to a stationary reference. As the shaft moves, the sensor reads the scale marks, which can be decoded to determine the angle of the object. Rotary encoders are commercially available ranging from 100 to 10,000 increments per revolution. A rotary encoder is schematically shown in Fig. 6.6.

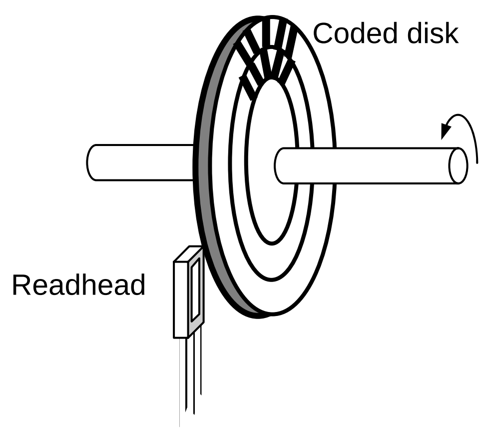


Figure 6.6 Rotary Encoder

Pre-Lab Exercises:

6-1. A Penny & Giles Sensor Model HLP 190 has an electrical stroke of 6 in. With an excitation of 8 V, the signal is measured as 6.3 V. Determine the transducer measurement?

6-2. A Penny & Giles Sensor Model HLP 190 has an electrical stroke of 6 in. The transducer is extended 4.25 inches with an excitation voltage of 15 V. The voltage of the signal is measured as 11 V. Determine the accuracy of the transducer?

6-3. A rotary potentiometer has an electrical stroke of 310 deg. With an excitation of 6 V, the signal is measured as 4.15 V. Determine the transducer measurement?

6-4. A rotary potentiometer has an electrical stroke of 290 deg. The transducer is displaced 135 deg with an excitation voltage of 9 V. The voltage of the signal is measured as 4.25 V. Determine the accuracy of the transducer?

Laboratory Experiences:

6-1. Determine the accuracy of linear displacement measurements.

a) Obtain a Penny & Giles LVRT and a steel rule.
b) Connect the transducer to a power supply and multimeter. (sketch set-up and accurately record equipment make and model numbers).
c) Determine the electrical stroke of the sensor. Think about this carefully.
d) Write a LabVIEW program to display the voltage output of the transducer and the linear displacement in appropriate units.
e) Use the multi-meter and DAQ to measure the output for various distances with various excitation voltages (do not exceed 10 volts).
f) Determine the accuracy of the transducer.
g) Determine the linearity of the transducer for the various linear displacements at various voltages.
h) Determine the repeatability of the transducer for the various displacements at various voltages.
i) As always, return equipment and clean-up workstation.

6-2. Determine the accuracy of angular displacement measurements.

a) Obtain a rotary potentiometer and a protractor.
b) Connect the transducer to a power supply and multimeter.
c) Determine the electrical stroke of the sensor. Think about this carefully.
d) Write a LabVIEW program to display the voltage output of the transducer and the angular displacement in appropriate units.
e) Use the multi-meter and DAQ to measure the output for various angles with various excitation voltages (do not exceed 10 volts).
f) Determine the accuracy of the transducer.
g) Determine the linearity of the transducer for the various displacements at various voltages.

h) Determine the repeatability of the transducer for the various angular displacements at various voltages.
i) As always, return equipment and clean-up workstation.

CHAPTER

7

TEMPERATURE MEASUREMENTS

7.1. Temperature

Temperature, T, is a property of a physical system that measures the thermal energy associated with the movement of particles in the system. In loose terms, temperature is a property of an object, or substance, which describes its hotness or coldness. As temperature increases, the atoms comprising an object will exhibit greater vibration from their equilibrium position. Temperature is important in that heat transfer will only occur between two objects if they are at different temperatures.

Temperature scales provide a reference and definition for a degree. The Celsius scale (^oC) is divides the interval between the freezing and boiling point of water into 100 equal parts. The zero point corresponds with the freezing point. The Fahrenheit scale (^oF) divides the interval between freezing and boiling point of water into 180 divisions, with 32 being the freezing point. The two scales can be converted by

$$^oF = 9/5\ (^oC) + 32 \qquad (7.1)$$

and conversely

$$^oC = 5/9\ (^oF - 32) \qquad (7.2)$$

Thermodynamics defines an absolute reference which is associated with the minimum amount of energy contained in an ideal gas. The notion of absolute zero temperature gives rise to two additional scales: Kelvin (^oK) and Rankin (^oR). These scales are often required in theoretical calculations, and some sensors are calibrated to them. These scales are related to the relative scales by

$$^oK = {}^oC + 273.16 \qquad (7.3)$$

and

$$^oR = {}^oF + 459.69 \qquad (7.4)$$

7.2. Temperature Measurements Based on Thermal Expansion

Liquid-in-Glass Thermometer

A liquid-in-glass thermometer uses the thermal expansion of a liquid to measure temperature as shown in Fig. 7.1. A bulb at one end contains a reservoir. The stem contains a capillary tube and calibrated marks etched along the tube. The level of the liquid provides an indication of the temperature. As the temperature increases, the liquid expands, and the level in the tube increases. Traditionally, mercury was widely used since it has linear expansion from –30 to 600 F. Due to toxicity of mercury, alcohol based substitutes are being used as a replacement.

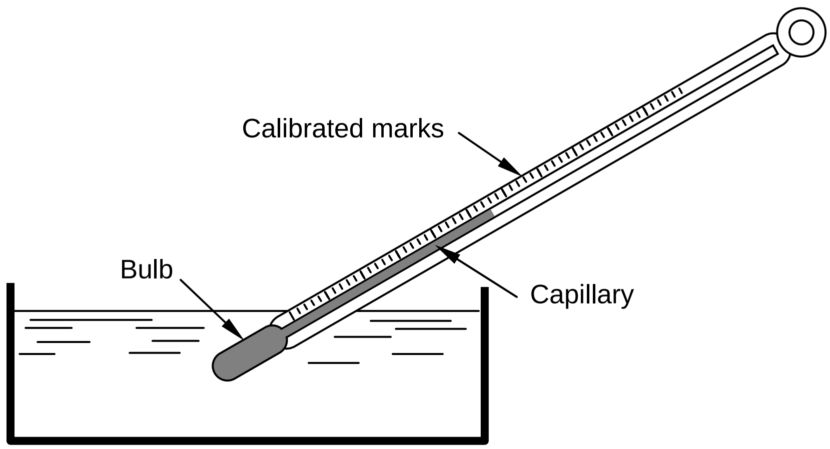


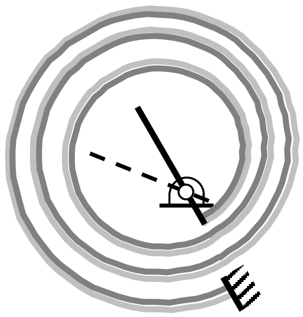
Figure 7.1: A glass-in-tube thermometer

Proper measurements require the entire bulb to be submerged in the medium being measured. A thermometer is a first-order response measurement system, and therefore, sufficient time must be allowed for the measurement to achieve equilibrium.

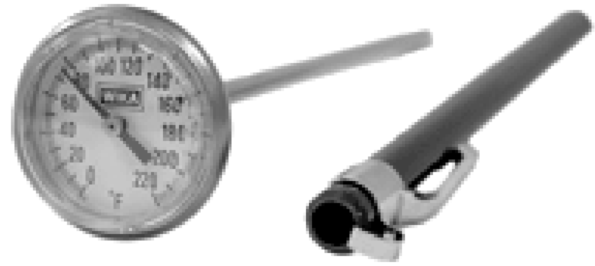
Bimetallic Thermometer

A bimetallic thermometer is based on the differential thermal expansion of two metals. Two metal strips with different coefficients of thermal expansion are bonded together. As the temperature increases, the strip with the higher thermal coefficient will expand more than the other strip. The bonded assembly will bend, triggering a mechanism that moves the arm on a dial. Calibrated marks on the face of the dial read the temperature. A schematic is shown in Fig 7.2a.

The bimetallic sensing element is used in most dial thermometers. In practice, the two materials are selected to achieve the desired deflection over a temperature range required for a certain application. A commercial bimetallic thermometer is shown in Fig 7.2b.



(a)



(b)

Figure 7.2: A bimetallic thermometer

7.3. Resistance Temperature Detectors

A physical characteristic of metals is that the electrical resistance increases with temperature. Resistance temperature detectors, or RTDs, are constructed by mounting a metal wire on an insulating support structure as shown in Fig. 7.3. The sensor is encased in a cover to protect the wire from the environment measurements will be taken. Platinum RTDs are most common and have developed a reputation for having accuracy over a wide temperature range (-200 to 850 ^oC), repeatability and stability.

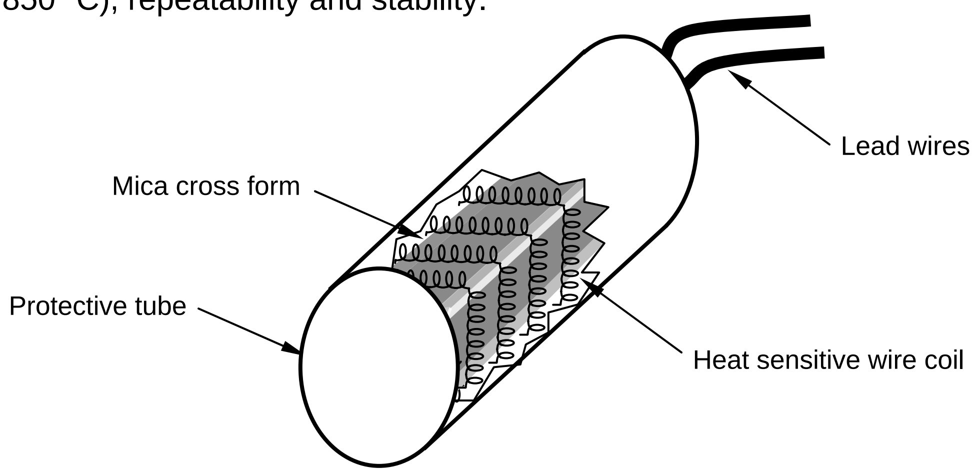


Figure 7.3: Construction of an RTD

The temperature based on the measured resistance, R_{RTD}, is nearly linear and determined with

$$T = \frac{1}{\alpha}\left[\frac{R_{RTD}}{R_0} - 1\right] + T_0 \qquad (7.4)$$

where the reference resistance, R_0, temperature, T_0, and coefficient or resistance, α, are given for a specific RTD. For the common platinum RTD, the American standard (used mostly in North America) has a resistance of 100Ω at 0^{o}C and a temperature coefficient of resistance of 0.00392 Ω/Ω/^{o}C. The European standard (used worldwide) for a platinum RTD has a resistance of 100Ω at 0°C and a temperature coefficient of resistance (α) of 0.00385 Ω/Ω/°C.

In an instrumentation system, a wheatstone bridge circuit is commonly used to convert the resistance change to voltage change..

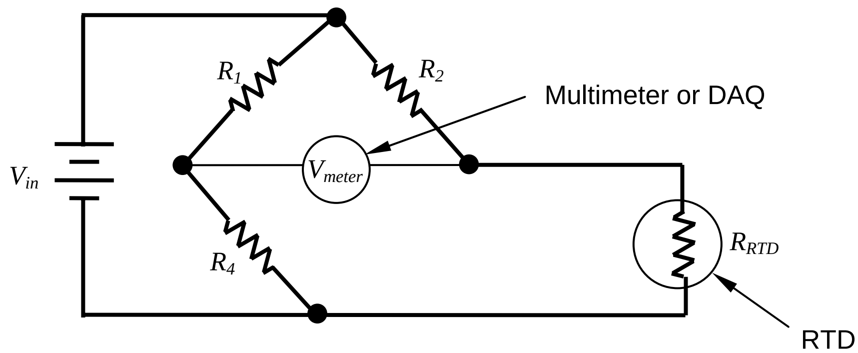


Figure 7.4: RTD completion circuit

The wheatstone bridge is usually constructed such that $R_1 = R_4$. In that case, the RTD resistance is calculated from the measured voltage of the completion circuit of Fig 7.4 as

$$R_{RTD} = R_2\left(\frac{V_{in} - 2V_{meter}}{V_{in} + 2V_{meter}}\right) \tag{7.5}$$

The calibration resistor R_1 in selected to obtain a voltage reading V_{meter} in a desired range, such as 0-5 volts.

7.4. Thermistors

Thermistors (thermally sensitive resistors) are semiconductor devises with a resistance that decreases rapidly with temperature. Thermistors are characterized with a fast response and high sensitivity over a rather narrow temperature range. They are often encapsulated in a glass, ceramic or metal shield so they can be used in corrosive environments. A commercial unit is shown in Fig. 7.5.

Figure 7.5: Thermistor

The consequence of the high sensitivity, a thermistor resistance is a non-linear function of temperature. The temperature is determined from the resistance of a thermistor with an empirical relationship of the form.

$$T = \frac{1}{a + b\,[\ln(R_T)] + c\,[\ln(R_T)]^3} \qquad (7.6)$$

where T is the temperature in Kelvin and $\ln(R_T)$ is the natural logarithm of the thermistor resistance, in Ohms. The coefficients a, b, and c, are determined from calibration data or tabulated for a specific thermistor.

Typical coefficients for commercial for thermistors are given in Table 7.1.

Table 7.1: Typical values for thermistor coefficients.

Resistance at Room Temp. (25 C)	*a*	*b*	*c*
1.00 kΩ	0.0013130	0.0002906	1.023E-07
2.00 kΩ	0.0010940	0.0002900	1.432E-07
2.25 kΩ	0.0014733	0.0002372	1.074E-07
3.00 kΩ	0.0014051	0.0002369	1.019E-07
5.00 kΩ	0.0012880	0.0002356	9.557E-08
6.00 kΩ	0.0012474	0.0002350	9.466E-08
10.00 kΩ	0.0011303	0.0002339	8.863E-08

In an instrumentation system, several different circuits can be used to convert the resistance change to voltage change. Since a thermister resistance change is substantial, a simple voltage is very common completion circuit and shown in Fig. 7.6.

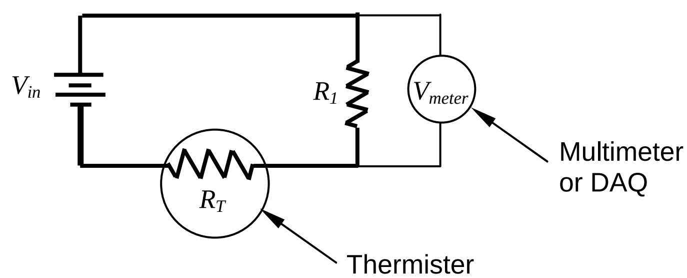


Figure 7.6: Thermistor completion circuit

The thermistor resistance is calculated from the measured voltage of the voltage divider completion circuit of Fig 7.4 as

$$R_T = R_1\left(\frac{V_{in}}{V_{meter}} - 1\right) \qquad (7.6)$$

The calibration resistor R_1 in selected to obtain a voltage reading V_{meter} in a desired range, such as 0-5 volts.

7.5. Thermocouples

The most common method of measuring and controlling temperature uses an electrical circuit called a thermocouple. The thermocouple is based on a thermoelectric, or Seebeck, effect. That is, when two wires of dissimilar metals are joined together to form a circuit of at least two junctions, a current will flow when the junctions are at different temperatures. The basic thermocouple circuit is shown in Fig. 7.5 can be used to measure the temperature difference between the two junctions.

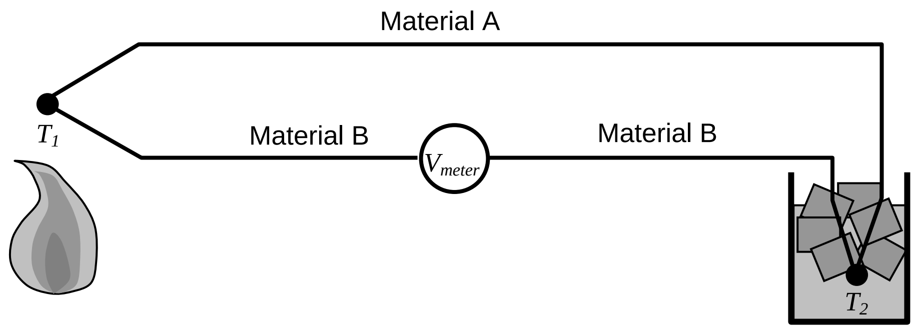


Figure 7.5: Basic thermocouple circuit

The thermoelectric effect allows the determination of the temperature difference of the two junctions. For practical measurements, one junction is designated a reference junction, and is maintained as some known reference temperature. Traditionally, the reference junction is placed in an ice bath (0 ^{o}C, 32 ^{o}F).

Electronic reference junctions provide a more convenient means of absolute measurements without the need for an ice bath. These generally rely on a thermistor to provide a reference temperature of one junction. Alternatively, data acquisition software allow a constant reference temperature input.

The National Institute for Standards and Technology (NIST) provides specifications for standard thermocouple wires for temperature measurements. Thermocouples are available in several different combinations of metals or calibrations. The four most common are J, K, T and E. Table 7.2 lists properties of the four common types.

Standard tables are available that can be used to convert the thermocouple output, in millivolts, to a temperature, in Celsius. An example for a J-type thermocouple is shown in Table 7.3.

Table 7.2: Common Thermocouple Types

Type	Positive	Negative	Range (^{0}C)	Features
E	Purple (Ni-Cr)	Red (Cu-Ni)	-270 to 1000	Highest voltage output, but larger drift
J	White (Fe)	Red (Cu-Ni)	-210 to 760	May rust. Can become brittle in sub-zero temperatures
K	Yellow (Ni-Cr)	Red (Ni-Al)	-270 to 1372	Most linear. Short life in oxidizing atmospheres
T	Blue (Cu)	Red (Cu-Ni)	-270 to 400	Superior corrosion resistance. Good for sub-zero use.

Table 7.3: J-type thermocouple calibration data

Temperature (°C)						Thermocouple voltage (mV)						
°C	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	°C
-40	-2.431	-2.385	-2.338	-2.291	-2.244	-2.197	-2.150	-2.103	-2.055	-2.008	-1.961	-40
-30	-1.961	-1.913	-1.865	-1.818	-1.770	-1.722	-1.674	-1.626	-1.578	-1.530	-1.482	-30
-20	-1.482	-1.433	-1.385	-1.336	-1.288	-1.239	-1.190	-1.142	-1.093	-1.044	-0.995	-20
-10	-0.995	-0.946	-0.896	-0.847	-0.798	-0.749	-0.699	-0.650	-0.600	-0.550	-0.501	-10
0	-0.501	-0.451	-0.401	-0.351	-0.301	-0.251	-0.201	-0.151	-0.101	-0.050	0.000	0
°C	0	1	2	3	4	5	6	7	8	9	10	°C
0	0.000	0.050	0.101	0.151	0.202	0.253	0.303	0.354	0.405	0.456	0.507	0
10	0.507	0.558	0.609	0.660	0.711	0.762	0.814	0.865	0.916	0.968	1.019	10
20	1.019	1.071	1.122	1.174	1.226	1.277	1.329	1.381	1.433	1.485	1.537	20
30	1.537	1.589	1.641	1.693	1.745	1.797	1.849	1.902	1.954	2.006	2.059	30
40	2.059	2.111	2.164	2.216	2.269	2.322	2.374	2.427	2.480	2.532	2.585	40
50	2.585	2.638	2.691	2.744	2.797	2.850	2.903	2.956	3.009	3.062	3.116	50
60	3.116	3.169	3.222	3.275	3.329	3.382	3.436	3.489	3.543	3.596	3.650	60
70	3.650	3.703	3.757	3.810	3.864	3.918	3.971	4.025	4.079	4.133	4.187	70
80	4.187	4.240	4.294	4.348	4.402	4.456	4.510	4.564	4.618	4.672	4.726	80
90	4.726	4.781	4.835	4.889	4.943	4.997	5.052	5.106	5.160	5.215	5.269	90
100	5.269	5.323	5.378	5.432	5.487	5.541	5.595	5.650	5.705	5.759	5.814	100
110	5.814	5.868	5.923	5.977	6.032	6.087	6.141	6.196	6.251	6.306	6.360	110
120	6.360	6.415	6.470	6.525	6.579	6.634	6.689	6.744	6.799	6.854	6.909	120
130	6.909	6.964	7.019	7.074	7.129	7.184	7.239	7.294	7.349	7.404	7.459	130
140	7.459	7.514	7.569	7.624	7.679	7.734	7.789	7.844	7.900	7.955	8.010	140

Curve-fit relationships have been developed from the calibration data of thermocouples and are of the form

$$T_2 - T_1 = C_0 + C_1 V + C_2 V^2 + C_3 V^3 + \ldots + C_7 V^7 + C_8 V^8 \qquad (7.7)$$

where T is (^{o}C) and V is (Volts). The coefficients for different thermocouples are given in Table 7.4.

Table 7.4: Thermocouple equation polynomial coefficients

	Type E Purple-Red	**Type J** White-Red	**Type K** Yellow-Red	**Type T** Blue-Red
	-100 to 1000 ^oC	0 to 760 ^oC	0 to 1360 ^oC	-160 to 400 ^oC
C_0	1.049672480E-01	-4.886825200E-02	2.265846020E-01	1.008609100E-01
C_1	1.718945282E+04	1.987314503E+04	2.415210900E+04	2.572794369E+04
C_2	-2.826390850E+05	-2.186145353E+05	6.723342480E+04	-7.673458295E+05
C_3	1.269533950E+07	1.156919978E+07	2.210340682E+06	7.802559581E+07
C_4	-4.487030846E+08	-2.649175314E+08	-8.609639149E+08	-9.247486589E+09
C_5	1.108660000E+10	2.018441314E+09	4.835060000E+10	6.976880000E+11
C_6	-1.768070000E+11		-1.184520000E+12	-2.661920000E+13
C_7	1.718420000E+12		1.386900000E+13	3.940780000E+14
C_8	-9.192780000E+12		-6.337080000E+13	
C_9	2.061320000E+13			

7.6. Radiative Temperature Measurements

All objects emit radiant energy, in the form of electromagnetic waves. At higher temperatures there is a greater amount of radiant energy emitted. Sometimes this energy appears as visible colors such as red hot steel or the tungsten of a filament lamp. Radiation thermometers can measure the temperature of an object by detecting the radiant energy being emitted.

There is a distinct advantage to detecting thermal radiation in that the sensor does not need to be in contact with the object being measured. Radiation thermometers are also referred to as non-contact thermometers. Thermal imaging and night vision apparatus use radiative temperature sensors to produce the image. Two of the more common types of radiation thermometers are radiometers and pyrometers.

Radiometers measures the source temperature by using a lens and focusing mirror to direct the radiation to a detector. The temperature of the detector is measured and calibrated to correspond with the temperature of the object emitting the radiation.

Optical pyrometers measure the temperature of an object my measuring the color of the radiation it emits. The amount of energy emitted is a function of temperature and the color of the object. Many pyrometers are pre- calibrated to measure a black object, with an emissivity of 1.

Most radiation thermometers are commercially sold with an integrated signal conditioning module. The output is linearized with a convenient conversion constant, such as 1 mV/^oC.

Pre-Lab Problems:

1-1. An RTD probe has a resistance of 100 Ω at 0^oC. The coefficient of resistance is 0.00392 $\Omega/\Omega/^oC$. Determine the resistance at 350 ^oC.

1-2. A European standard RTD is connected to a Wheatstone bridge, with all other resistors have values of 100 Ω. The supply voltage is 3 V and the bridge output is -0.5 V. Determine the temperature being measured.

1-3. During calibration testing, the following resistances and reference temperatures have been measured

Trial	Temperature (^oC)	Thermistor resistance (Ω)
1	100	5477.7
2	125	2812.3
3	150	1604.9

Determine the thermistor a, b, and c, coefficients.

1-4. A 6 kΩ thermistor is configured in a voltage divider circuit with a 200 Ω calibration resister. A 2 V input is applied to the circuit. The thermistor is placed as a control sensor in a soldering oven. The meter voltage is recorded as 168 mV. Determine the temperature of the soldering oven. Also, compute the power dissipated by the 200Ω resistor.

1-5. A 3 kΩ thermistor is to be used with a voltage divider circuit and a data acquisition system. A 5 volt input into the thermister completion circuit is desired. Determine a calibration resistor that will give a 2 volt output at room temperature.

1-6. A J type thermocouple is immersed in an engine oil reservoir, and a reference junction is placed at 0 ^oC. The thermocouple generates 2.2 mV. Use Table 1.3 to determine the temperature of the oil.

1-7. A K type thermocouple is placed in a sintering furnace. The reference junction is placed at 25 ^oC. The thermocouple generates 34.1 mV. Use the thermocouple curve-fit equation to determine the temperature of the oil.

1-8. A J type thermocouple is to be used in an application where the temperature will vary from 45 ^oF to 150 ^oF. Determine an appropriate input voltage range for a data acquisition system.

1-9. An infrared pyrometer is to be used in an application where the temperature will vary from 45 ^oF to 150 ^oF. The output of the pyrometer is 1 $mV/^oC$. Determine an appropriate input voltage range for a data acquisition system.

Laboratory Experiments:

7-1. Determine the accuracy of temperature measurements:

a) Create a LabVIEW program to accept two analog voltages:
   - one from a thermocouple
   - one from a thermister, used with a voltage divider circuit.

b) Fill your hotpot with water.

c) Prepare an ice bath solution for the reference junction of the thermocouple.

d) Use a hotpot and ice to alter the temperature of the water.

e) Measure the temperature of the water using:
   - Mercury-in-glass thermometer
   - Bimetallic thermometer
   - Thermocouple, measuring voltage with DAQ
   - Thermocouple, calibrated with handheld multimeter
   - Thermister and a voltage divider circuit, measuring voltage with DAQ.

   Since most temperature measuring equipment are first-order devices, allow some time to converge to the measurement.

f) Repeat measurements at several other temperatures. At some point during your testing, make sure the water is boiling.

g) By comparing the measurements, determine the accuracy of different methods.

h) As always, assist in the lab cleanup.

CHAPTER

8

STRESS AND STRAIN MEASUREMENTS

8.1 Stress

In solid mechanics, stress, σ, is a measure of the average amount of force carried by an object per unit area. In other words, it is a measure of the intensity of internal forces acting within a body. Stress is an important measure, since materials are only able to handle a certain amount before failure.

Uniaxial stress is when the material is experiencing stress in one primary direction. Biaxial stress has the material experiencing stress in two orthogonal directions. A general state of stress has the internal forces acting within the material in all directions.

Bending is a primary form of stress. It occurs when a long part is loaded perpendicular to its length. A common structure component is a cantilever beam, and is shown in Fig. 8.1. A cantilever beam is fixed on one end and free on the other. The geometry is specified by a total length, L, and cross sectional properties. In the case of a rectangular beam shown in Fig. 8.1, the base, b, and height, h, are important parameters.

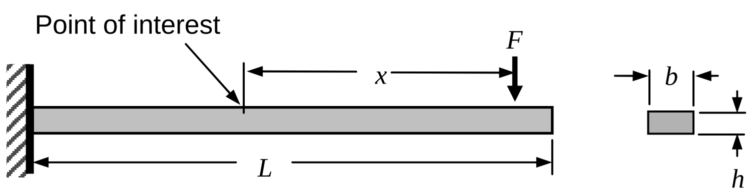


Figure 8.1: Cantilever Beam

The top fibers are being stretched and experiencing tension. The theoretical stress that is induced on the top fibers at the point of interest designated by x is

$$\sigma = \frac{6\,F\,x}{b\,h^2} \qquad (8.1)$$

The bottom fibers experience compression. The value of stress on the compression side of a cantilever beam is determined as the negative of Eq. 8.1.

8.2 Strain

In solid mechanics, strain, ε, is a measure of the relative deformation created by stress. Strain is a dimensionless quantity and often is cited as a percentage or in parts-per notation, such as “inches per inch”. Since strain is a small value, micro-strain (1 in/in = $1\text{x}10^6$ micro-strain) is also frequently cited.

For uniaxial stress, strain can be related to through Hooke’s Law

$$\sigma = E\varepsilon \qquad (8.2)$$

The proportionality constant is the modulus of elasticity, E. This is an experimentally determined material property, and values given in Table 8.1.

Table 8.1: Modulus of Elasticity for Some Materials

Material	Modulus of Elasticity
Aluminum	10.6×10^6 psi
Copper	18.0×10^6 psi
Steel	30.0×10^6 psi

For biaxial stress, the relationship to strain is more complex, and involves Poisson’s ration, ν,

$$\sigma_x = \frac{E}{1-\nu^2}(\varepsilon_x + \nu\varepsilon_y) \qquad (8.3)$$

$$\sigma_y = \frac{E}{1-\nu^2}(\varepsilon_y + \nu\varepsilon_x) \qquad (8.4)$$

8.3 Strain Gage

A very common device for the electrical measurement of mechanical quantities is the strain gage. Physically, a strain gage takes advantage the dependence of electrical conductance on the conductor's geometry. When an electrical conductor is stretched, it will become longer and thinner, increasing its electrical resistance. Conversely, when a conductor is compressed it will become shorter and thicker, decreasing its electrical resistance. If a conductor, such as a wire shown in Fig. 8.2, is firmly glued to a structural member, the conductor will deform with the member. By measuring the electrical resistance of the conductor, the amount of stress in the member can be inferred.

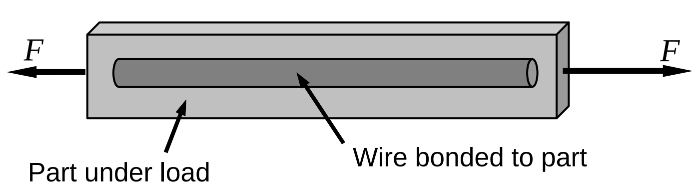


Figure 8.2: Wire glued to a structural member

A typical strain gage is arranged as a long, thin conductive strip in a zig-zag pattern of parallel lines. This arrangement permits a small amount of strain to be magnified by a multiply large amount of deformation of the conductor. Thus, small amounts of strain in the direction of the parallel lines results a multiplicatively larger change in resistance.

The bonded resistance strain gage is by far the most widely used in experimental stress analysis, and shown in Fig. 8.3. These gages consist of a grid of very fine foil bonded to the carrier matrix. In use, the carrier matrix is firmly glued to the surface of a structural member. As force is applied, the strain is found by measuring the change in resistance.

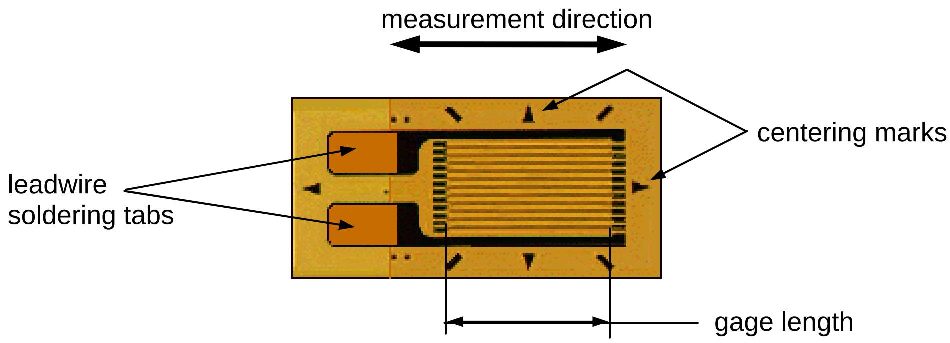
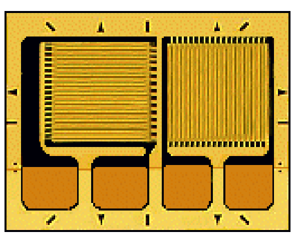


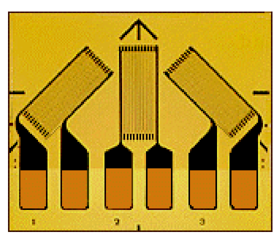
Figure 8.3: A bonded strain gage

The bonded resistance strain gage is low in cost, can be made with a short gage length, is only moderately affected by temperature changes, has small physical size and low mass, and has fairly high sensitivity to strain. They are commercially available in 120 Ω and 350 Ω configurations, with gage lengths ranging from 0.015 to 2.00 inch.

To assess complex stress fields, bonded strain gages are also available in biaxial and rosette patterns. These styles are essentially multiple gages mounted on the same carrier matrix as shown in Fig. 8.4. They are able to detect strain in multiple directions.



(a) Biaxial



(b) Rosette

Figure 8.4: Strain gage with alternate patterns

8.4 Strain Gage Resistance Measurements

The fundamental strain gage equation that relates the strain to the change of resistance, ΔR, from an unstressed condition and the unstressed gage resistance, R,is

$$\varepsilon = \frac{(\Delta R)}{(R)}\left[\frac{1}{GF}\right] \qquad (8.5)$$

Strain gages are constructed to have a particular gage factor, GF. For many common 120Ω gages, GF = 2.1.

Strain may be detected by directly measuring the change of resistance of a gage, while the structure is loaded. A multimeter, set to resistance measurements, can perform this function. While measuring strain through direct resistance is uncomplicated, small resistance changes are difficult to accurately measure. Therefore, directly measuring resistance changes is not recommended when precise results are required.

Completion Circuit
Alternatively, the strain gage can be placed into a voltage divider circuit as shown in Fig. 8.5.

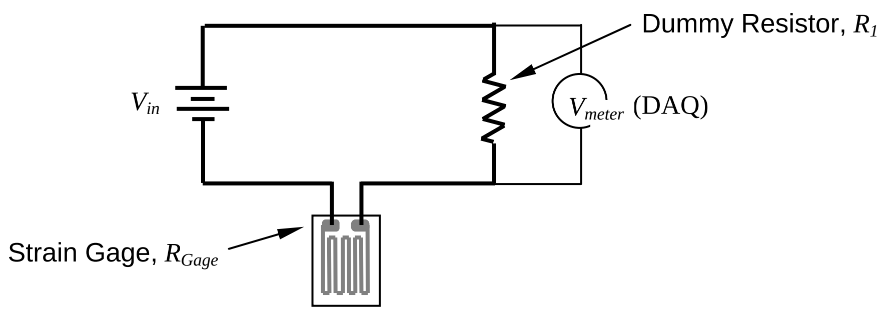


Figure 8.5: Strain gage in voltage divider circuit

Using a circuit as shown in Fig. 8.5, the change of resistance is converted to a change of voltage detected at the meter. This allows data acquisition. The resistance of the gage is calculated from the meter voltage from the voltage divider equation

$$R_{Gage} = R_1\left(\frac{V_{in}}{V_{meter}} - 1\right) \qquad (8.6)$$

The resistance of the dummy gage is selected to adjust the meter voltage in a desired range.

8.5 Strain Gage Bridge Measurements

Quarter Bridge

A Wheatstone bridge arrangement is particularly effective for use with strain gages because it can easily be adjusted to zero voltage for zero strain and provides a means for temperature compensation. Figure 8.6 shows a bridge arrangement where one arm consists of the strain gage mounted on a test piece, and dummy resistors comprise the other arms. This arrangement is termed a quarter-bridge completion circuit.

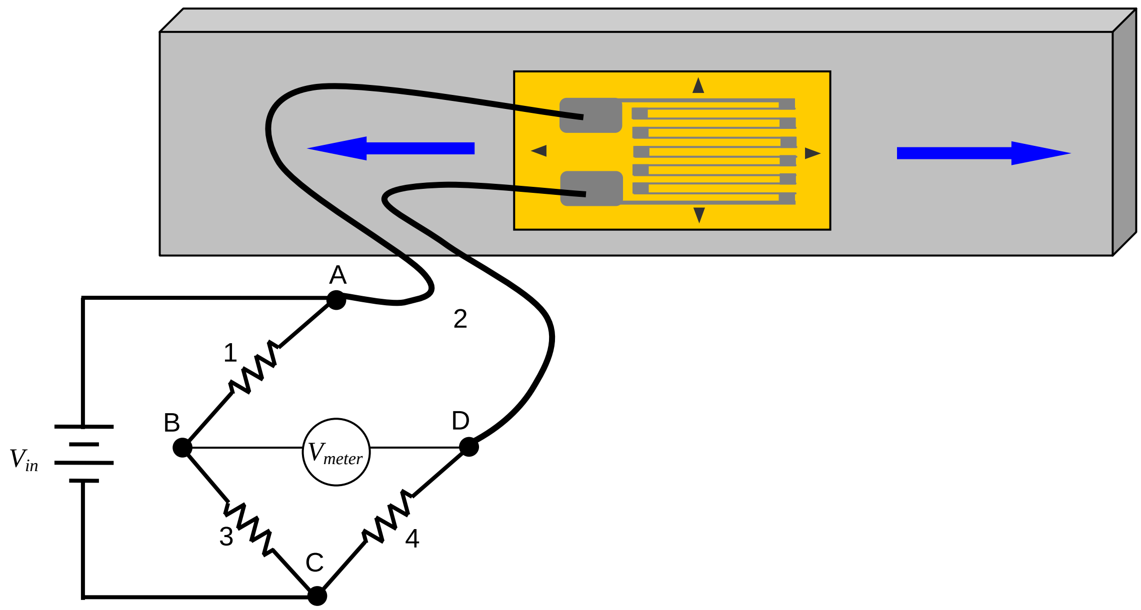


Figure 8.6: Quarter-bridge strain gage circuit

The strain can be calculated from the change in the measured voltage of the quarter bridge completion circuit as

$$\varepsilon = \frac{4(\Delta V_{meter})}{(V_{in})}\left[\frac{1}{GF}\right] \qquad (8.7)$$

While there is no standard, an excitation voltage, V_{in}, level of around 3 and 10 V are common. A higher excitation voltage generates a proportionately higher output voltage, which gives greater sensitivity. However, higher voltage can also cause larger errors because of self-heating because more power is dissipated through the resistance of the gage.

Imbalance

In practice, the gage and dummy resistors will not be perfectly matched. Therefore, the meter will detect a voltage even as no load is applied to the structure. This is termed imbalance. The imbalance should be subtracted from the all subsequent readings.

In a more eloquent treatment of imbalance, a balance circuit can be constructed as shown in Fig 8.7 and discussed in Chapter 2. With this circuit, a potentiometer can be adjusted to eliminate, or null, the initial meter voltage reading.

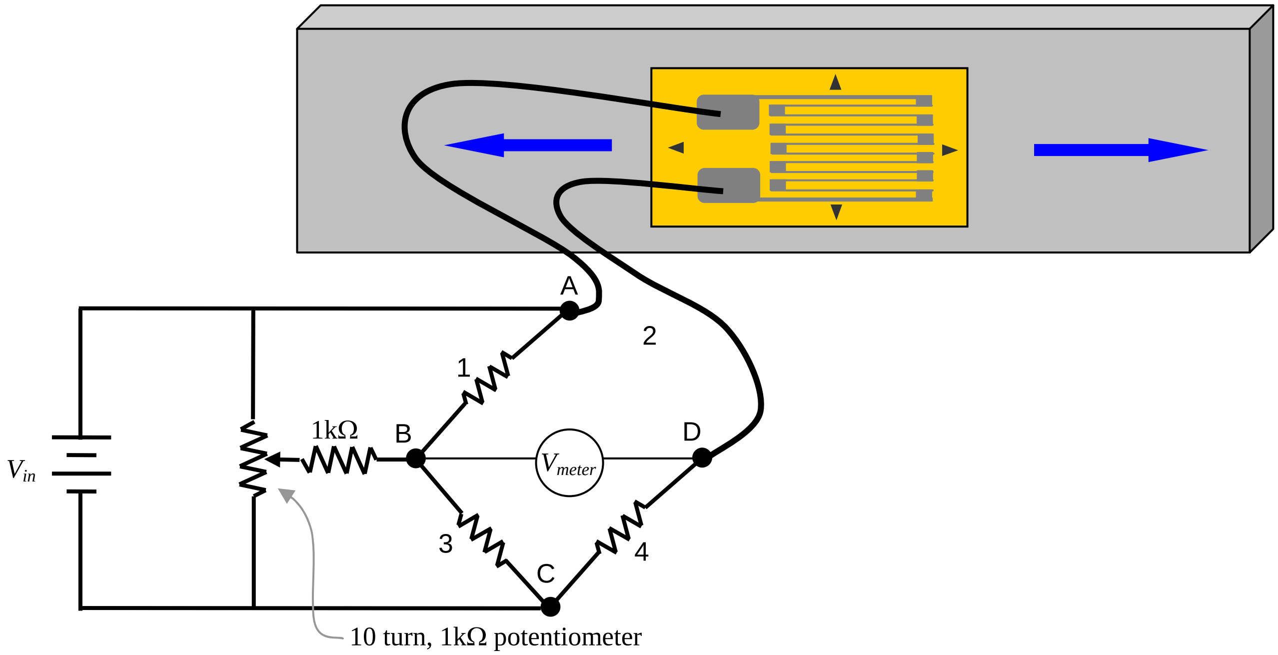


Figure 8.7: Quarter-bridge strain gage circuit with balance compensation

Lead Wire Compensation

Frequently, the strain gage and the data acquisition unit must be separated by an appreciable distance. In these cases, long lead wires must be used. To compensate for the resistance of the lead wires, or temperature gradients that exist along the wires, a third lead can be used as shown in Fig. 8.8. The resistance of the lead wires will cancel, and the effect of long lead wires will be eliminated.

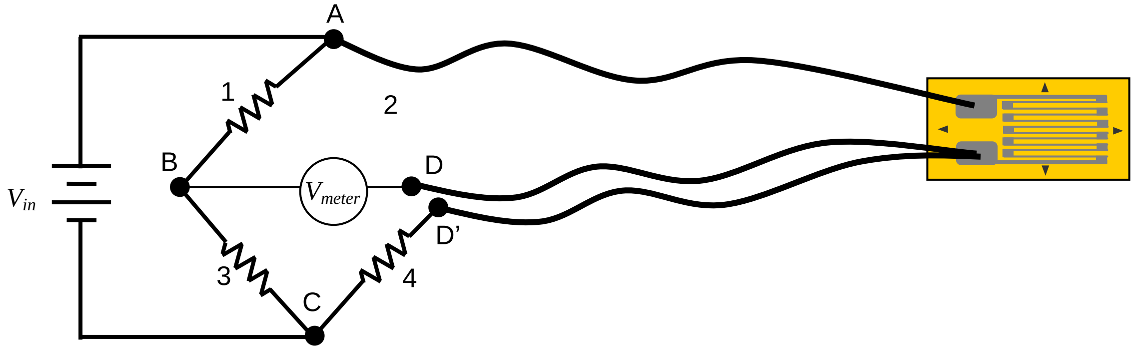


Figure 8.8: Lead wire compensation

Half Bridge

In many cases, the bridge configuration permits the use of more than one arm for measurement. This is particularly true if a known relationship exists between two gages. One common situation is a part in bending, where the section is symmetrical about the neutral axis. The tension and compression strains are equal, except for the sign. In this situation, gages on the top and bottom can be used as two arms in the bridge as shown in Fig 8.9.

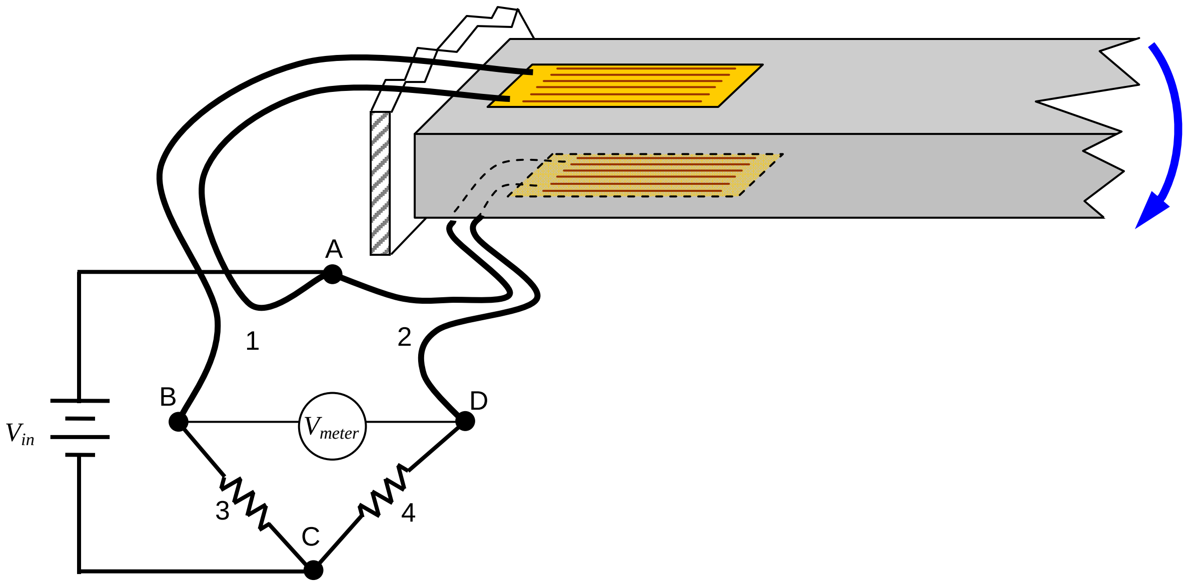


Figure 8.9: Half-bridge strain gage circuit

When the beam in Fig 8.9 is loaded, the resistance changes will be alike, but with an opposite signs. Properly placing the gages into the bridge will double the bridge output, and increase accuracy by reducing the effects of noise. In this case, the strain level can be calculated from the change in the measured voltage of the half bridge completion circuit as

$$\varepsilon = \frac{2(\Delta V_{meter})}{(V_{in})}\left[\frac{1}{GF}\right] \qquad (8.8)$$

As with the quarter bridge, imbalance will be observed when a physical half bridge, strain gage circuit is constructed. Thus, an output voltage even as no load is applied to the structure. The imbalance should be subtracted from the all subsequent readings. Alternatively, a balance circuit can be constructed for the half bridge circuit as shown in Fig 8.10.

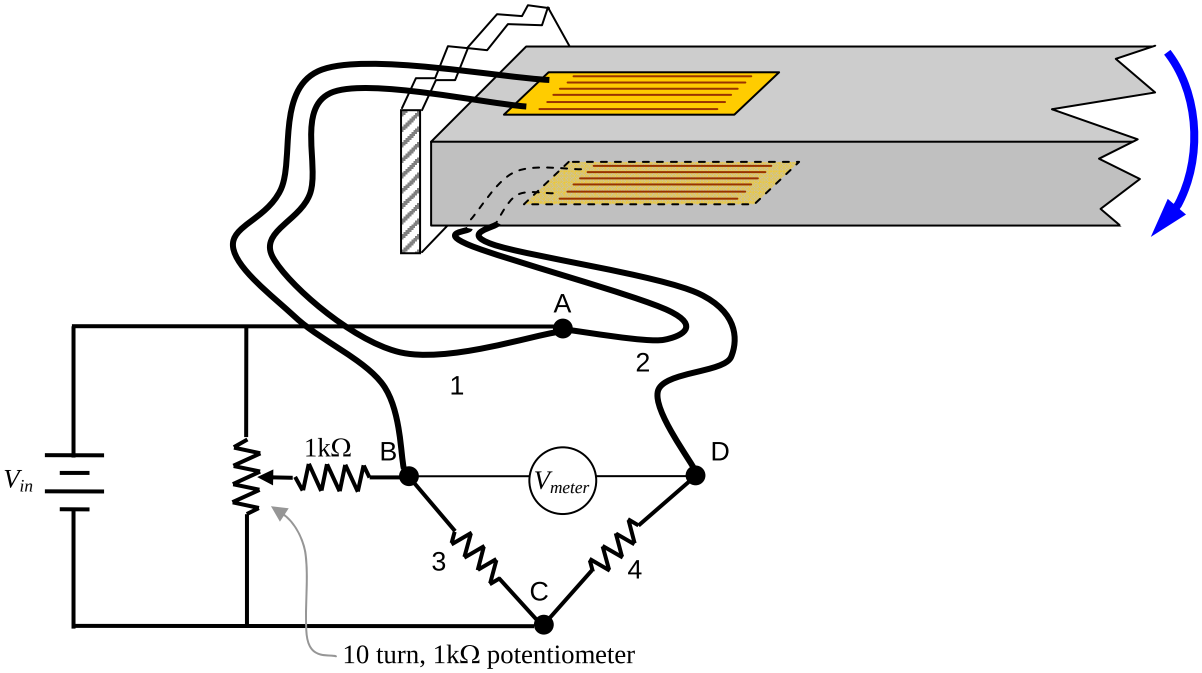
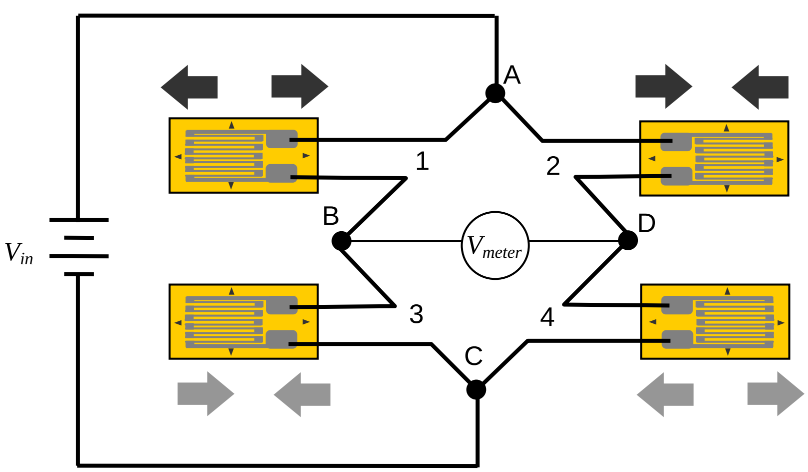


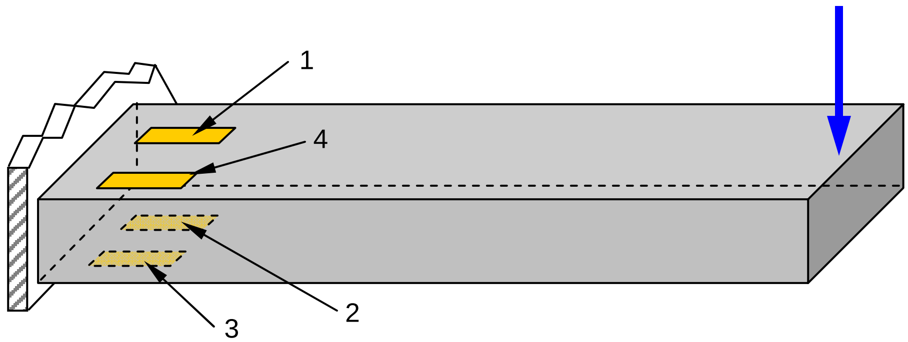
Figure 8.10: Half-bridge strain gage circuit with balance compensation

Full Bridge
Extending the rationale of the previous section, all four arms of the bridge can be made strain-sensitive which would quadruple the bridge output. In this configuration, gages 1 and 4 would be wired to record like strain (such as tension) and gages 2 and 3 to record the opposite strain (such as compression). Two examples of a beam wired into a full bridge is shown in Fig. 8.10.

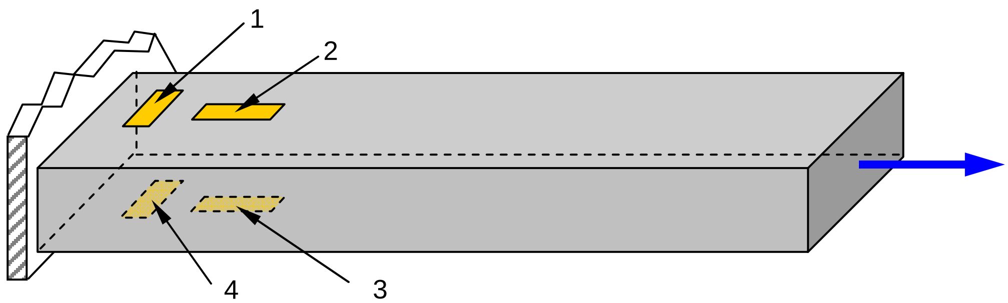


(a) Circuit description

Figure 8.10: Full-bridge strain gage circuit



(b) Beam in bending



(c) Beam in direct tension or compression

Figure 8.10: Full-bridge strain gage circuit (con't)

8.6 Strain Gage Calibration

Since strain gages small resistance changes, the output of strain gage bridges is relatively small. In practice, most strain gage bridges output less than 10 mV/V (10 mV of output per volt of excitation voltage). With 10 V excitation, the full scale output signal is 100 mV. Therefore, strain gage signal conditioners usually include amplifiers to boost the signal level to increase measurement resolution and improve signal-to-noise ratios.

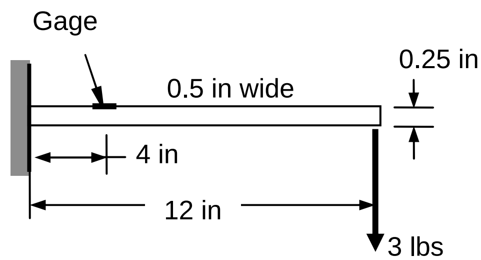
For signal conditioners with a variable amplification, the gain is usually selected to provide a convenient reference system, such as 5 volts output at 5000 psi stress level. To vary the output in this manner, the strain gage should be calibrated with known loads prior to usage.

Pre-lab Problems:

8.1 A 500 lb load is applied to a bar, 2 inches long. The bar stretches 0.005 in. Determine the strain.

8.2 A strain gage is mounted on a steel automotive suspension part. The original resistance is measured as 118.36 Ω. As the part is loaded, the resistance is measured as 118.42 Ω. Determine the strain and stress being measured in the part.

8.3 A steel beam is loaded as shown. A 120Ω strain gage measures an increase of 0.04 Ω when loaded. Determine the accuracy of the gage.



8.4 A 120 Ω strain gage is placed in a divider circuit with another 120 Ω resistor. A 5.0 volt source is placed across both resistors, and 2.5 V is measured across the dummy resistor. Once the gage is loaded, the voltage across the dummy resistor reduces to 2.496 V. Determine the change of resistance of the strain gage.

8.5 The steel beam from Problem 8.3 is loaded as shown. A 120Ω strain gage is wired into a quarter bridge completion circuit. A 10V input is placed across the bridge. Before loading the beam, an output of 0.72 mV is detected. Once the load is applied, an output of 1.52 mV is measured. Determine the accuracy of the gage.

Experiments:

8.1 Determine the accuracy of strain gages using direct resistance measurements.

a. Clamp a beam onto the bench top to simulate a cantilever beam. Do not allow clamp to damage the strain gage!

b. Measure the initial resistance of the tension and compression strain gages.

c. Obtain two resistors, and precisely measure their resistance.

d. Configure two separate voltage divider circuits, one for each strain gage.

e. Write a LabVIEW program that:

   i. Accepts the resistance of the two dummy resistors, and the original resistances of the gages.

   ii. Acquires the voltage placed on the divider circuits, and the voltage across the two dummy gages

   iii. Determines the resistance change, and the strain being measured for each gage.

f. Place weights on the beam, and determine theoretical strain developed at the gage.
g. Compare to the experimental strain measured through LabVIEW.
h. Change the location of the load and repeat the above steps.
i. Comment on the accuracy, repeatability and linearity of the strain gages.
j. Comment on any other trends and observations that were made.
k. As always, return equipment and clean-up workstation

8.2 Determine the accuracy of strain gages using a Wheatstone bridge completion circuit.

a. Clamp a beam onto the bench top to simulate a cantilever beam. Do not allow clamp to damage the strain gage!
b. Use three 120Ω resistors, and the strain gage on the beam as the fourth resistor, and construct a wheatstone bridge on a breadboard.
c. Place a voltage across the bridge. (do not exceed 10 volts)
d. Write a LabVIEW program to accept the input into the bridge and the output voltage from the bridge. Since these are static measurements, take the average. Write these two voltages along with the load and application distance to a file.
e. Take measurements of both the tension and compression strain gages, at several loads, distances, and bridge input voltages. Always include a zero load to determine the imbalance for that bridge input voltage.
f. Calculate the theoretical strain values at each load setting.
g. Determine the accuracy of the gages.
h. Comment on the accuracy, repeatability and linearity of the gages.
i. Comment on any trends that are observed:
   i. Is the accuracy better at higher or lower strain levels?
   ii. Is the accuracy better at higher or lower input voltages?
j. As always, return equipment and clean-up workstation.

Chapter

9

FORCE, TORQUE AND PRESSURE MEASUREMENTS

9.1 Force Measurement

A force is a push-pull action. Understanding the forces involved in a machine is important as excessive values will destroy components. Since forces in machine components are difficult to accurately determine through analytical means, especially where vibration and impact are involved, measurement becomes an important task. Common applications of force measurement in automation systems require accurate determination of weight, such as filling and dispensing stations. In other instances, insertion tools on assembly machines often push with a specified amount of force.

9.2 Spring Force Gauge

A spring force gauge is simply a spring fixed at one end with a hook to attach an object at the other. The force required to extend a spring is linearly dependant on the deflection of the spring. Therefore the markings on the spring scale are equally spaced. Gauges range from a simple coil extension spring(Fig 9.1a) to precision torsional spring and gear mechanisms (Fig 9.1b).

(a)

(b)

Figure 9.1 Spring Force Gauges

9.3 Strain-Gage Load Cells

A load cell is a term to describe a transducer that generates a voltage signal as the result of an applied force. Such transducers consist of an elastic member that deflects is a predictable fashion as load is applied. Linear deflection with an applied force is a critical design feature of the load cell. An "S" style load cell as shown in Fig. 9.2 is a common geometric configuration. Canister, beam, multiple bending and ring configurations are also common. A sensor detects the deflection and is calibrated to correlate with the applied force. The majority of commercially available load cells use strain gages as the sensing element. Strain gages are presented in a following chapter.

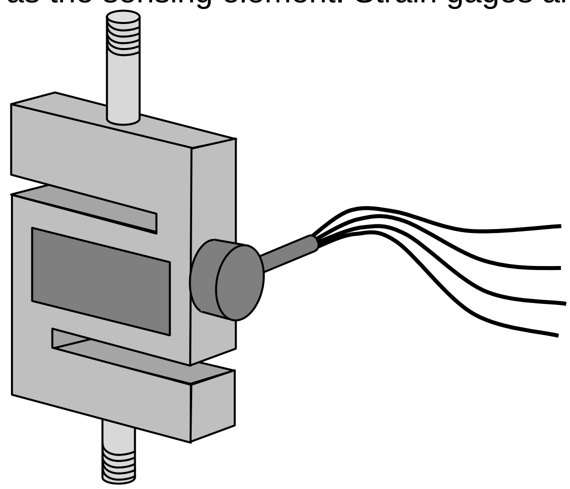


Figure 9.2 Load Cell

Load cells have four lead wires, two for an excitation voltage, and two contain the signal. A common wiring scheme has been adopted among manufactures as shown in Fig. 9.2.

Excitation voltage, $V_{excitation}$, is usually limited by heating considerations to a maximum of 10 volts for transducers constructed with 120-ohm strain gages. For transducers that use 350-ohm strain gages, excitation up to 20 volts is possible. However, good practice dictates somewhat lower values.

A transducer has a rated capacity, F_{max}, which should be selected to fit the specific application. The transducer sensitivity, K, is expressed in millivolts per volt (mV/V) at full capacity. The value of K is measured at the time of manufacture and is furnished with the transducer. For example, the *Omega LC101-50* is 3 mV/V at 50 lb.

In practice, it is difficult to completely balance the internal sensor circuit. This means that a voltage will be measured across the green and white wires, even without loading the transducer. This initial reading is termed imbalance, and will need to be subtracted from successive measurements, to determine the effective transducer signal, V_{signal}.

To calculate the measured force, F, the following relation can be used:

$$F = F_{\max}\left\{\frac{V_{signal}\left(1000\ \mathrm{mV/V}\right)}{K\,V_{excitation}}\right\} \qquad (9.1)$$

As discussed in Chapter 2, circuits can be constructed that eliminate the imbalance. A balance circuit applied to a load cell is shown in Fig. 9.3. Alternatively, balance circuits are integrated into most signal conditioners, as will be discussed in the next section.

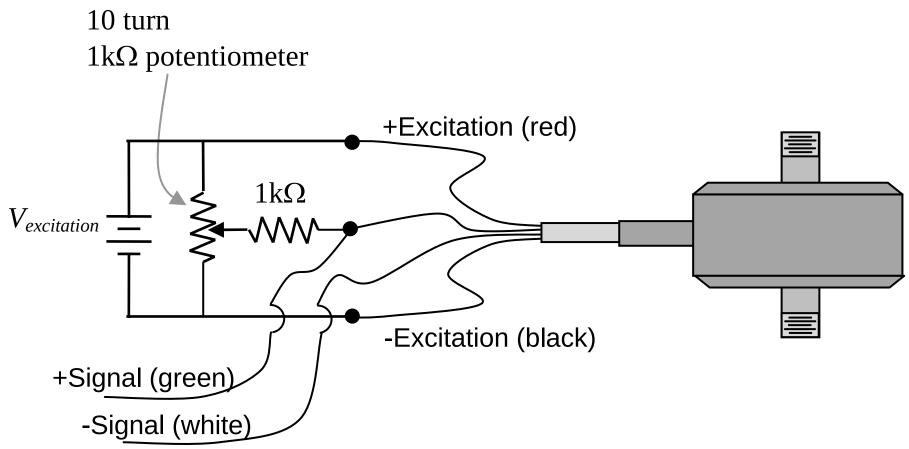


Figure 9.3 Load Cell Balance Circuit

9.4 Transducer Instrumentation

The signal from a strain-gage load cell is low voltage, usually a few millivolts. Thus, measurement systems using load cells usually require signal conditioning, which includes amplification and filtering. Signal conditioning is discussed detail in Chapter 5. The gain on the signal conditioner is usually adjusted to achieve a convenient output, such as 5 volts is 50 lbs. Many signal conditioners include a balance potentiometer to eliminate imbalance. A *Transducer Technique TMO-2 Load Cell Signal Conditioner* is shown in Fig. 9.4.

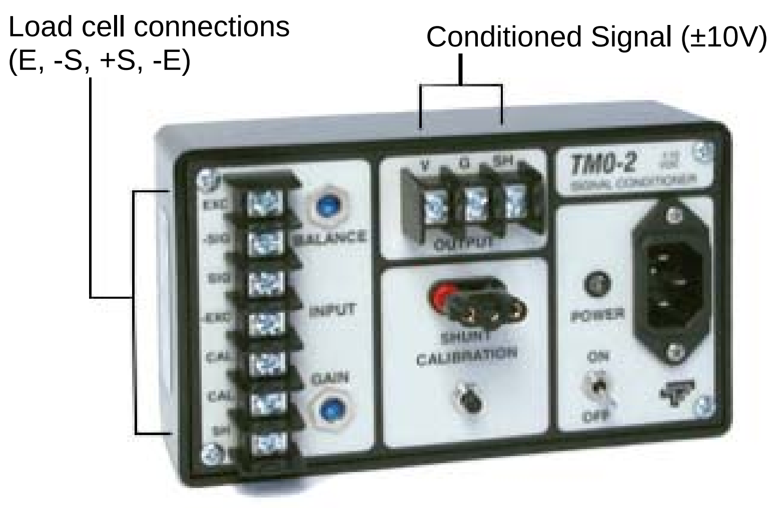


Figure 9.4 Commercially Available Load Cell Signal Conditioner

9.4 Transducer Calibration

A load cell measurement can be calibrated by placing multiple known loads onto the system and recording the output signal. A representative calibration curve is shown in Fig. 9.5. Note that a calibration curve is only valid for a single excitation voltage.

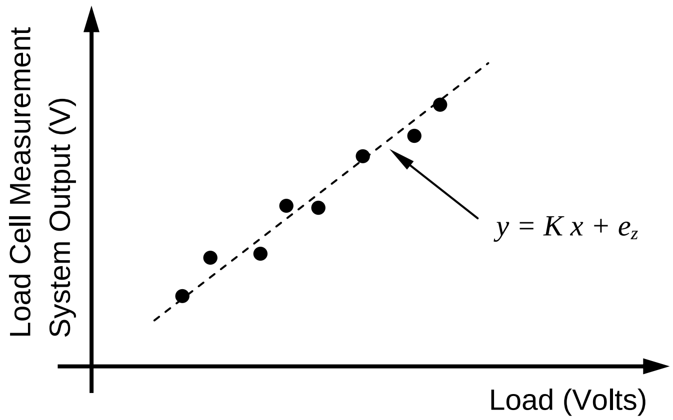


Figure 9.5 Calibration Curve

Sensitivity
The slope of the calibration curve is the sensitivity, K, of the transducer measurement system. The sensitivity relates the change in signal to a change in load. It is best determined as the least-squares slope from a curve fit of the calibration data. Curve fit was presented in Chapter 1.

Range
A proper procedure for calibration is to apply loads ranging from the minimum to maximum allowable values for the measurement system. The input span, R_i, is the operating range of loads applied to the measurement system.

$$R_i = x_{max} - x_{min} \qquad (9.2)$$

Similarly, the full-scale-operating range, R_o or FSO, is the range of the signal observed.

$$FSO = R_o = y_{max} - y_{min} \qquad (9.3)$$

Zero Shift
The zero shift, e_z, is the y-intercept of the calibration curve. Many instrumentation systems have the balance potentiometer, which can eliminate the zero shift. If the imbalance cannot be eliminated through hardware, it is best determined as the least-squares intercept from a curve fit of the calibration data. Curve fit was presented in Chapter 1.

Once calibration data is collected and the curve-fit analysis is complete, the information can be used in the data acquisition stage of the measurement as shown in Fig 9.6.

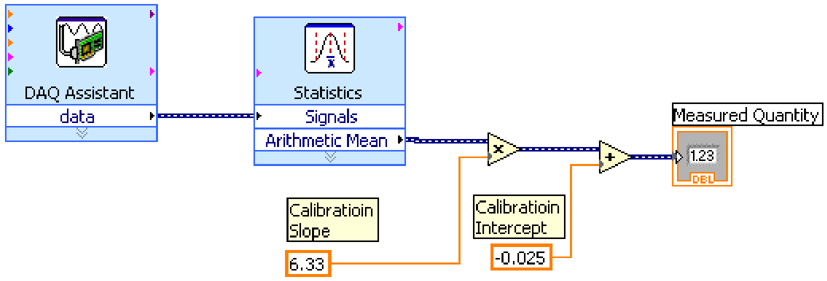


Figure 9.6 Calibration Data Incorporated into LabVIEW

9.5 Shunt Calibration

A normal procedure to verify the output of a load cell and signal conditioner measurement system is called shunt calibration. Shunt calibration involves simulating a force by changing the resistance of the transducer circuitry by some known amount. Shunting, or connecting, a large resistor across two leads of the transducer creates a known change of resistance.

As an example, the manufacturer of a *Transducer Techniques MLP-1K* load cell states that placing a 87.3 kΩ resistor across the –E (black wire) and –S (white wire) will provide the same signal as a 450 lb load. Additionally, a 43.6 kΩ resistor across the –E (black wire) and –S (white wire) will provide the same signal as a 900 lb load. Using these two points, the output from a signal conditioner can be verified. If the signal conditioner output is not as expected, the gain or offset can be adjusted appropriately.

Shunt calibration is accepted throughout the industry as means of periodic calibration of a signal conditioner and transducer between calibrations of known, applied, traceable, mechanical, input values. Consequently, most all strain gage transducer manufacturers supply shunt calibration data, along with shunt calibration resistors, as a standard feature.

9.6 Piezoelectric Load Cells

Loads cells that use piezoelectric crystals are effective for measuring forces that change abruptly. The transducer produces an electrostatic charge in terms of coulombs per unit load, with 10 to 20 pC/lb being typical. The transducer output is conditioned through a charge amplifier and produces a signal voltage that is proportional to the charge. Advantages include a wide range of working load, excellent frequency response, great stiffness, high resolution and small size. An important limitation is that piezoelectric devices are inherently a dynamic sensor. Long-term static output stability is weak.

9.7 Torque Measurement

Torque is a twisting action caused by a force offset by a distance, as shown in Fig. 9.7.

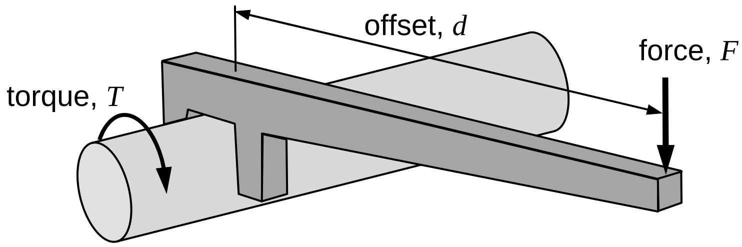


Figure 9.7 Torque

Torque and force are related through

$$T = Fd \qquad (9.4)$$

Torque measurement is accomplished in a similar manner to force, with strain-gage transducers being the most common. Torque transducers are rated in an identical manner to load cells. The wire connections, instrumentation and calibration are equivalent. Two types of torque transducers are available:

Reaction Torque Transducer

A reaction torque sensor takes advantage of Newton's third law: “for every action there is an equal and opposite reaction”. To measure the torque produced by a motor, we could measure it inline, or we could measure how much torque is required to prevent the motor from turning, commonly called the reaction torque. Without moving pieces, reaction torque measurement is much more straightforward. Strain gages are placed in the transducer to sense the twisting action. Reaction torque transducers come in a wide variety of form factors including shaft, solid flange (as shown in Fig. 9.8), hollow flange and flat types.

Figure 9.8 Reaction Torque Transducer

Rotary Torque Transducer

A significant challenge to measuring torque on a rotating shaft is in dealing with the transducer lead wires. Two primary means of transmitting data from the rotating shaft are employed. The tradition manner is using slip rings. Slip rings are composed of several rotating cylindrical electrical conductors which are rigidly attached to the shaft. A circuit is formed through sliding contacts with stationary brushes.

Telemetry can also be used to transmit signals from sensors on a rotating shaft. Such telemetry systems use radio frequencies and operate in a manner similar to other wireless devices.

Figure 9.9 Rotating Torque Transducer

9.8 Pressure Measurement

Pressure is the average force exerted on a fluid per unit area. Pressure is most commonly expressed in terms of pounds-per square inch (psi), or pascals (Pa). Pressure measuring devices include the following.

Manometers
An ordinary manometer is the most elementary pressure measuring devices. The manometer is simply a column of liquid, where the height differential is a indication of the difference of pressure. A manometer is shown in Fig 9.10.

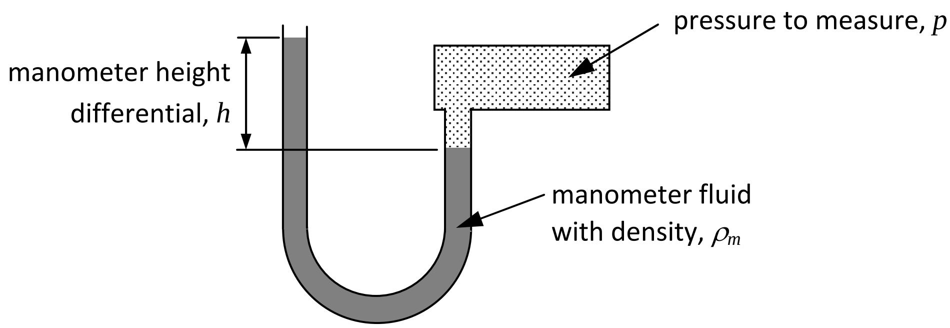


Figure 9.10 Manometer

The pressure measured with a manometer is calculated from the measured height differential.

$$\Delta p = \rho_m \, g \, h = \gamma_m \, h \qquad (9.5)$$

In Imperial units, the weight density, γ_m, is more often cited. While it is simple and inexpensive, the manometer has a limited pressure range for reasonable column lengths, and a poor dynamic response.

Bourdon Tube Gage

A Bourdon tube gage operates on the principle that the deflection of a pressurized tube can be used to measure pressure. A Bourdon tube is shown in Fig 9.11. A tube normally of oval section is initially coiled into a circular arc. As a pressure is applied within the tube, it tends to uncoil. The motion of the end of the tube is communicated through a linkage and gearing to a pointer whose movement over a scale becomes a measure of pressure.

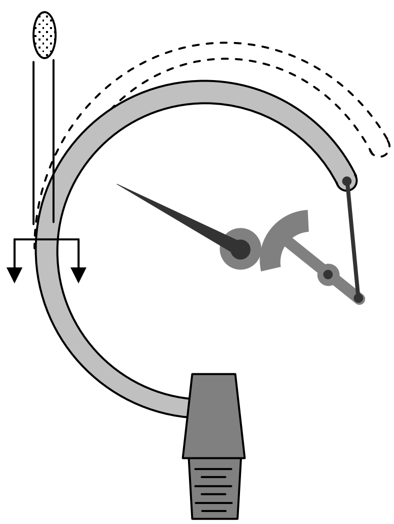


Figure 9.11 Basic Bourdon Tube

Strain-gage Pressure Transducers

In a similar manner to force, electronic pressure measurements are made with strain-gage transducers being the most common. Pressure transducers are rated in an identical manner as load cells.

The most common configuration of pressure transducers is ato apply strain gages directly to a diaphragm surface and calibrate the measured in terms of pressure. A diaphragm style transducer that can be calibrated to measure the pressure difference is shown in Fig. 9.12.

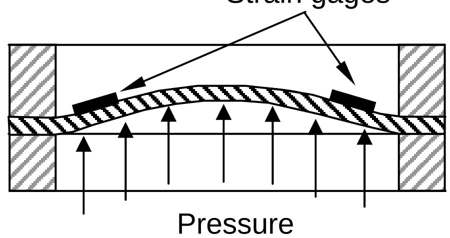


Figure 9.12 Differential Pressure Transducer

Pre-Lab Exercises:

9.1. A force transducer has the following specifications:

Omega LC101-100:

Output at Rated Capacity................	*3 mV/V*
Capacity...	*100 lbs.*
Max. Excitation Voltage.................	*15V*
Useable Temperature Range.............	*0 to 200^0 F*

With an excitation voltage of 10 volts, an imbalance of 0.0026 V is observed. As the transducer is loaded, the voltage of the signal is measured as 0.0173 V, what is the transducer reading?

9.2. A torque transducer has the following specifications:

Sensor Development Model 1051

Output at Rated Capacity................	*2 mV/V*
Capacity...	*20 ft lbs.*
Max. Excitation Voltage.................	*20V*
Useable Temperature Range.............	*0 to 200^0 F*

An excitation voltage of 7.5 V is applied to the transducer and a 0.0032 V signal is observed. If 150 in lb is applied to the transducer, the voltage of the signal is measured at 0.0167 V. Determine the accuracy of the transducer ?

9.3. A water (ρ = 62.4 lb/in^3) filled manometer is used to measure the pressure in an air tank. A 32 inch differential is measured in the manometer legs. Determine the pressure in the tank.

9.4. A water (ρ = 62.4 lb/in^3) filled manometer is used to measure the pressure in an air tank. The pressure is expected to vary from 15 psi to 30 pis. Determine the appropriate leg length for the manometer.

9.5. A pressure transducer has the following specifications:

Sensor Development Model 1051

Output at Rated Capacity................ 2 mV/V
Capacity... 80 psi.
Max. Excitation Voltage................. 20V
Useable Temperature Range............. 0 to 200^0 F

An excitation voltage of 10 V is applied to the transducer and a 0.0016 V signal is observed. If 50 psi is applied to the transducer, the voltage of the signal is measured at 0.0183 V. Determine the accuracy of the transducer.

Laboratory Experiences:

9.1. Determine the accuracy of force, torque or pressure transducers.

a) Acquire a force, torque or pressure transducer. Note the sensitivity (mV/V) and capacity (lbs, in-lbs, etc.) of the transducer
b) Connect the power supply (excitation) to the transducer input leads and to DAQ.
c) Connect the output leads (signal) of your transducer to the handheld multimeter and to DAQ.
d) Make a note of the imbalance of the transducer at this source voltage.
e) Write a LabVIEW program to:
    i. accept and display the excitation voltage and the signal voltage.
    ii. subtract the imbalance and compute the mechanical measurement (force, torque) in appropriate units.
    iii. compare the measurement to the actual applied load
    iv. send all these values to a file.
f) Use this program to measure the transducer output for various loads (do not exceed sensor capacity) with various source voltages (do not exceed 10 volts). Note that the imbalance will change with source voltage.
g) Determine the accuracy, repeatability and linearity of the transducer.
h) Comment on any trends that are observed.
    - load/torque/pressure vs. accuracy
    - input voltage vs. accuracy
    - repeatability vs. load or input voltage
    - linearity of transducer
i) As always, return equipment and clean-up workstation

Chapter

10

ANGULAR VELOCITY MEASUREMENTS

10.1 Angular Velocity

Angular velocity, ω, is defined as the time rate of change in the angular position, θ, of an object.

$$\omega = \frac{d\theta}{dt} \cong \frac{\Delta\theta}{\Delta t} \qquad (10.1)$$

Angular velocity is also referred to as rotational speed, and specified in radians per second (rad/s), rotations per minute (rpm) or rotations per second (rps).

Measurement of angular velocity provides an indication of the speed of a shaft. The primary application of angular velocity measurements is in closed-loop, speed control systems. In these systems, the speed of a shaft is monitored and compared to a desired value. The input to the prime mover is adjusted to achieve the desired speed. Speed control is used on devices from automotive “cruise control” to CNC milling machines and other automation equipment.

Sensors that detect angular velocity also provide a means to measure translational velocities, which can be transformed to rotation motion for measurement by gearing or pulley systems.

10.2 DC Motors

An electric motor uses electrical energy to create an interaction of magnetic fields and current carrying conductors. The magnetic attraction can be employed to produce mechanical energy through a rotating shaft. A direct current (dc) motors are commonly used to power mechanical devices because the speed and direction can be easily altered.

With no load, the speed of a dc motor is proportional to the supplied voltage, V_S.

$$\omega \cong k_V V_s \qquad (10.2)$$

The velocity constant, k_V, is a feature of a specific motor. An example motor speed curve is shown in Fig. 10.1. The polarity of the supplied voltage determines the direction of rotation (clockwise or counterclockwise).

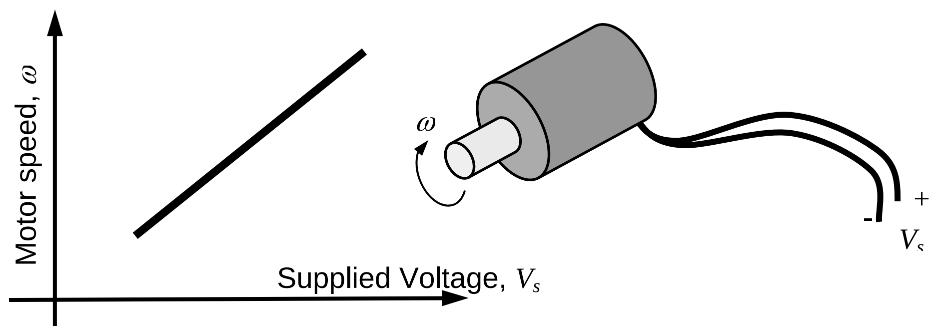


Figure 10.1 DC Motor Speed Curve

10.3 Angular Velocity Measurement Methods

An electric motor uses electrical energy to create an interaction of magnetic fields and current carrying

Contact Tachometer
A contact tachometer is a device that combines a counter and timer, along with circuitry to provide a display directly in rpm. The counter determines the rotation of the shaft in a certain amount of "refresh" time. The shaft of the tachometer must be held in firm contact with shaft being measured. A common contact tachometer is shown in Fig. 10.2.

Figure 10.2 Contact Tachometer

Stroboscope
A stroboscope is a device that produces rapid flashes of high-intensity light at a precise frequency. A timing mark on a rotating object can be made to appear slow moving or stationary. The instrument is used to determine the speed of a rotating object by adjusting the strobe to “freeze” the timing mark. Once an object appears stationary, the flashes are synchronized with the rotational speed. If the stroboscope is not quite synchronized with the object's motion, the object will appear to move slowly either backward or forward, depending upon whether the stroboscope's rotation is too fast or too slow. A common stroboscope is shown in Fig. 10.3.

Figure 10.3 Stroboscope

When using a stroboscope, the timing mark will appear motionless when the flashing frequency is an integer multiple of the rotational speed. In practice, once the image is frozen, the flashing frequency should be halved. If the image appears twice, the prior frequency was synchronized with the shaft speed. If the image remains frozen, the flashing frequency should be halved until a double image is observed.

Photoelectric Sensors
A photoelectric sensor can detect the presence or absence of light. Flashes of light synchronized with a rotating object are detected by a photoelectric receiver. The frequency of the light received is proportional to the speed of the object being measured. Most photoelectric receivers can be configured as normally open or closed. A schematic of a photoelectric speed measuring setup is shown in Fig. 10.4.

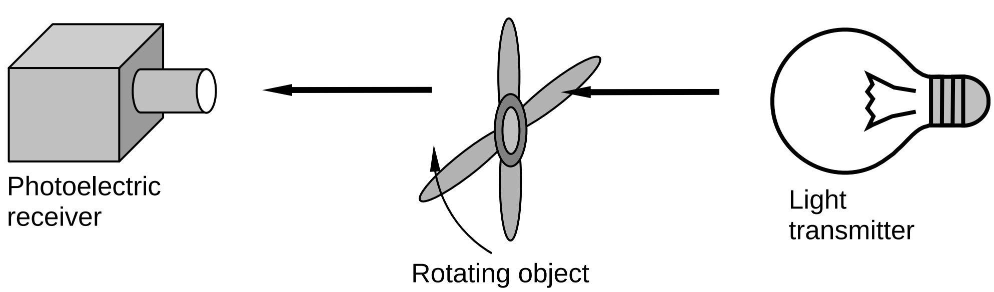


Figure 10.4 Photoelectric speed measuring setup

A reflective speed measurement system can be configured by placing reflective material on the target. A schematic of a retroreflective photoelectric speed measuring setup is shown in Fig. 10.6.

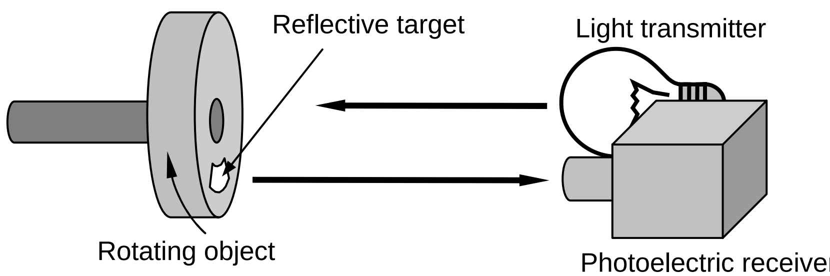
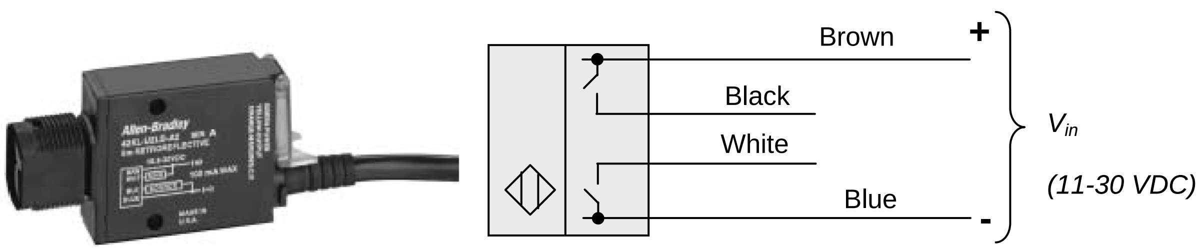


Figure 10.6 Photoelectric speed measuring setup

Photoelectric sensors intended for automation systems have a light transmitter and photoelectric receiver packaged together. Some commercial models, along with their wiring diagrams, are shown in Fig. 10.7.

Allen Bradley MiniSight



AMTEK 836/SXA

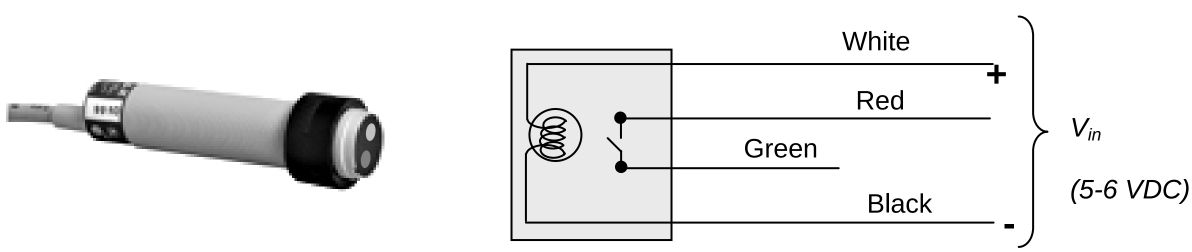


Figure 10.7 Photoelectric sensors

Handheld photoelectric tachometers have an integrated circuit to count the flashes during a certain time, and display the results in rpm. Reflective stickers are supplied and adhered to the rotating object being measured. A commercially available photoelectric tachometer is shown in Fig. 10.8.

Figure 10.8 Photoelectric tachometer

Proximity Sensor

A proximity sensor detects the presence of nearby objects without making contact. An inductive proximity sensor consists of a coil around an iron core. When energized, the coil produces an electromagnetic field. As a metal object passes through the field, energy is absorbed into the object. The sensor detects this loss of energy and turns “on” a solid-state switch. Figure 10.9 shows a proximity sensor with gear teeth being used as a target.

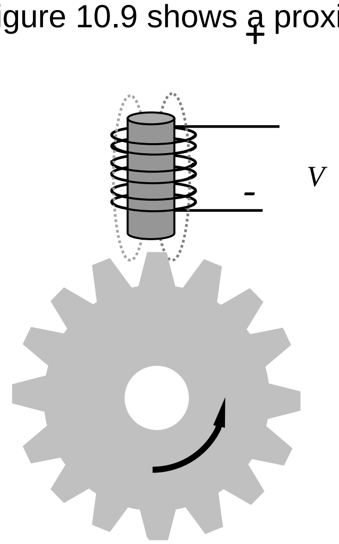


Figure 10.9 Photoelectric tachometer

Capacitive sensors operate similarly, and have the advantage of not requiring a metallic target. In capacitive proximity sensors, the sensed object changes the dielectric constant between two plates. Because changes in capacitance take a relatively long time to detect, the upper switching range of a proximity sensor is about 50 Hz. Along with measuring angular velocity, capacitive proximity sensors are also being used as touch buttons on electronic devices.

Some commercial models of inductive proximity sensors, along with their wiring diagrams, are shown in Fig. 10.9.

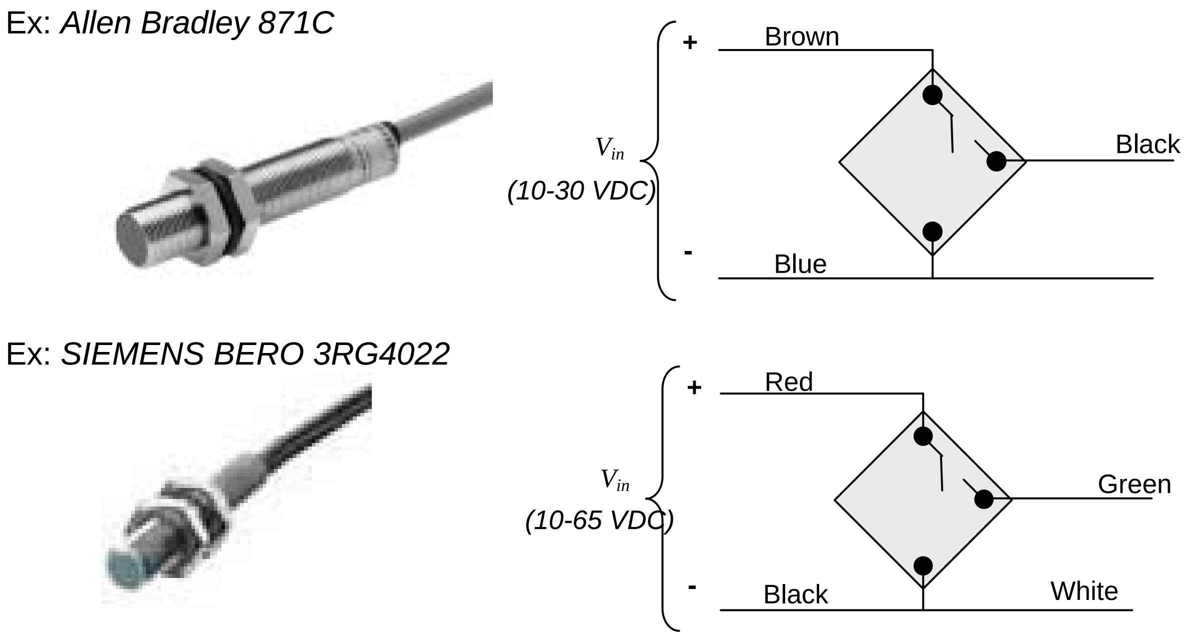


Figure 10.10 Commercial Proximity Sensors

Digital Optical Encoder
An encoder converts the angular position of a shaft to a digital code. As shown in Fig. 10.11, the encoder has an enclosed series of photo-detectors that work with a coded disk to convert motion into a sequence of digital pulses.

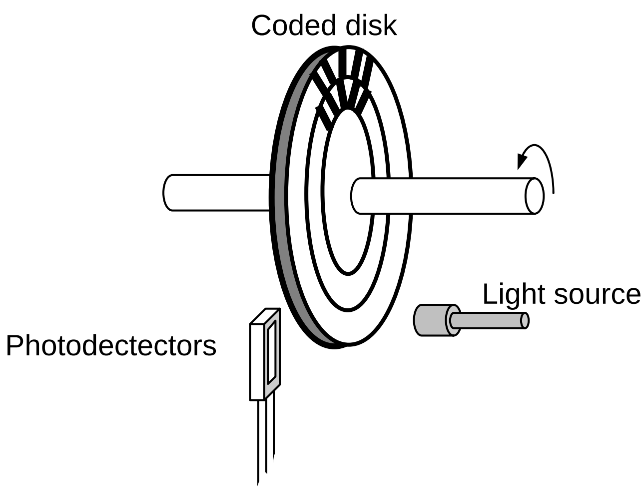


Figure 10.11 Digital Optical Encoder

The encoder output includes two digital outputs called quadrature outputs as they at 90 degrees out of phase. The two quadrature outputs, shown in Fig. 10.12, can be decoded to direction.

A Channel

B Channel

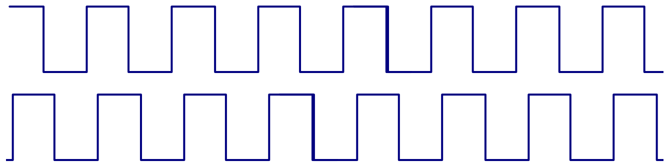
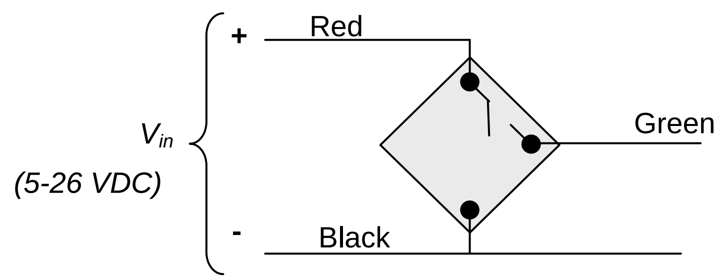


Figure 10.12 Quadrature Output

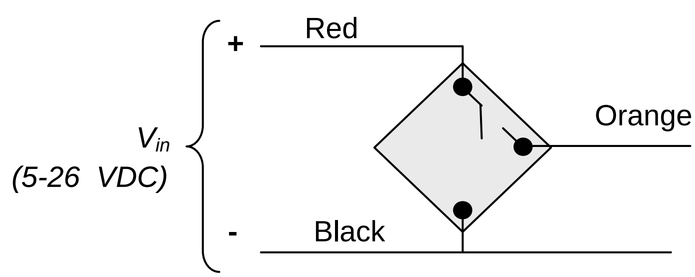
A commercial model, along with its wiring diagram, is shown in Fig. 10.13.

Dynapar22-0100 (100 pulses per revolution)

For the "A Signal"



For the "B Signal"



Signal A leads B for clockwise shaft rotation

Figure 10.13: Commercial Rotary Encoder

10.4 Signal Frequency and Angular Velocity

For the sensors that detect the presence of an object on a shaft, the signal generated by the sensor appears as a square wave. The angular velocity can be determined from the frequency, f, of the sensor signal. Occasionally, it is easier to work with the period, T, of the sensor signal. Very often, multiple objects are present for each revolution of the shaft designated with the pulses per revolution, p. One such setup is shown in Fig. 10.14.

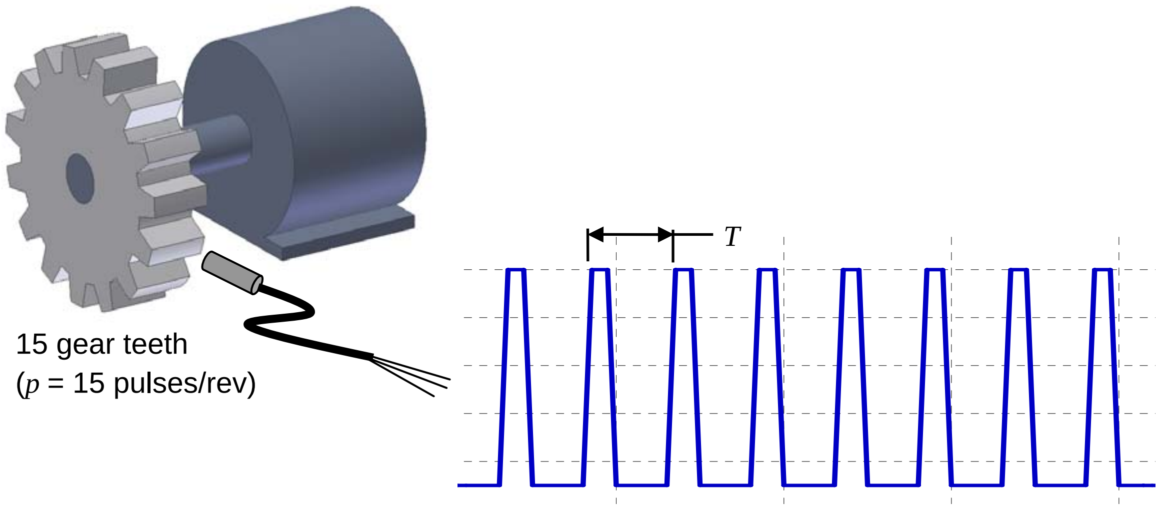


Figure 10.14: Angular Velocity Sensor Signal

The angular velocity can be calculated as

$$\omega = \frac{f}{p} = \frac{1}{T\ p} \qquad (10.3)$$

10.5 Preparing the Sensor Output for DAQ

Since most angular velocity sensors require a relatively high source voltage, the output voltage of the sensor can often be greater than the limits on the DAQ system (10 V). The dynamic signal can be stepped down with a simple circuit, without altering the frequency response. A wiring diagram of the Minilight photoelectric tachometer used with a voltage divider circuit is shown in Fig. 10.15. The values of the two resistors should be selected to achieve the desired voltage reduction.

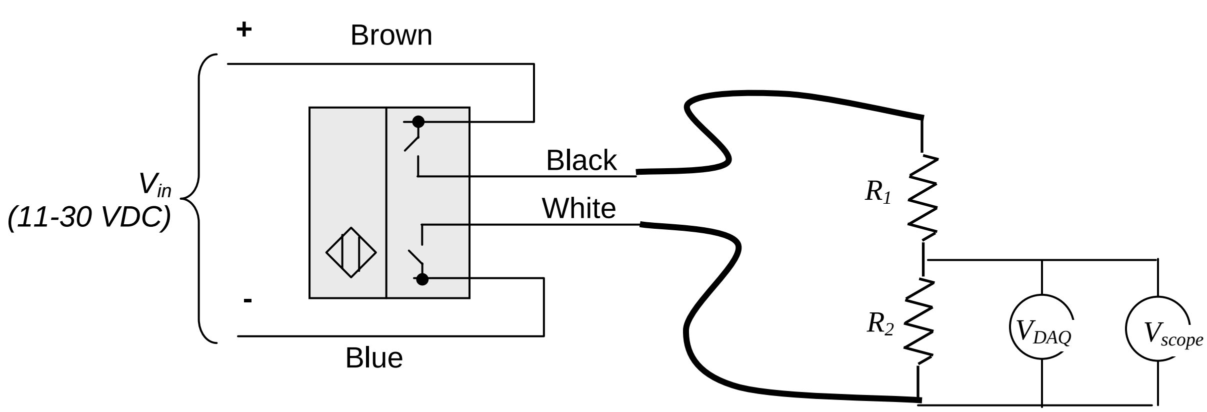


Figure 10.15: Voltage Divider with the Minilight Photoelectric Tachometer

A wiring diagram of the Allen-Bradley proximity sensor used with a voltage divider circuit is shown in Fig. 10.16. Again, the values of the two resistors should be selected to achieve the desired voltage reduction.

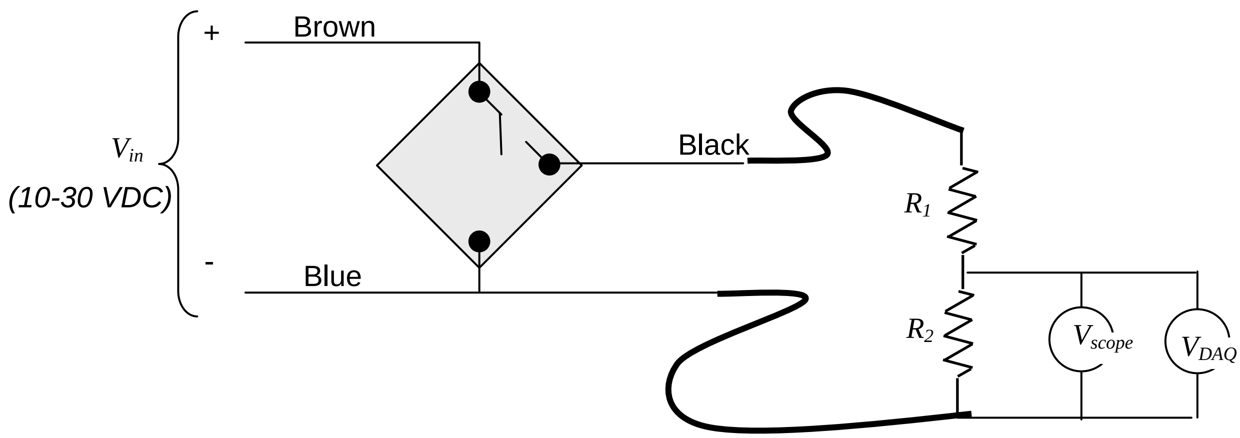


Figure 10.16: Voltage Divider with the A-B Proximity Sensor

Pre-Lab Exercises:

10-1. A 15 tooth gear rotates on a motor shaft. A proximity pickup is used to detect the each gear tooth, producing a signal with a period of 0.015 seconds. Determine the motor RPM.

10-2. A 32 tooth gear rotates on a motor shaft. A proximity pickup is used to detect the each gear tooth, producing a signal with a frequency of 1900 Hz. Determine the motor RPM.

10-3. A photoelectric sensor is used to detect the presence of four reflectors attached to a disk, which is in turn fastened to a motor shaft. As the motor is powered, a tone measurement determined that the sensor signal had a frequency of 76.4 hz. Determine the motor RPM.

10-4. An encoder that generates 100 pulses per revolution is used to precisely measure the speed of a shaft. The maximum speed is expected to be approximately 2000 rpm. Determine an appropriate sampling rate for a data acquisition system that will accept the encoder signal.

Laboratory Experiences:

10-1. Determine the accuracy of natural frequency measurements.

a) Use a large C-clamp to fixture a cantilever beam.
b) Write a LabVIEW program to capture a finite waveform and use spectral analysis to measure the dominant frequency.
c) Use LabVIEW to measure the natural frequency of the beam from a:
    i. strain gage (signal conditioned).
    ii. piezoelectric.
    iii. piezoresistive (signal conditioned)
d) Repeat measurements at several (at least 6) other cantilever lengths.

e) Calculate the theoretical natural frequency for the different lengths used.
f) Observe accuracy tendencies and trends for vibration frequency measurements.
g) As always, assist in the lab cleanup.

Chapter

11

VIBRATION MEASUREMENTS

11.1 Acceleration

Acceleration, a, is defined as the rate of change of velocity, v, of an object, or a point on an object. It is also related to the position, s, of an object

$$a = \frac{dv}{dt} = \frac{d^2 s}{dt^2} \qquad (11.1)$$

Over short time intervals, the acceleration of an object can estimated as

$$a \cong \frac{\Delta v}{\Delta t} = \frac{2\left(\Delta s - v_0 \Delta t\right)}{\Delta t^2} = \frac{v - v_0}{2\Delta s} \qquad (11.2)$$

Acceleration is often expressed relative to the acceleration due to gravity (g = 9.81 m/s^2 = 386.4 in/s^2). For example, a 5g acceleration is 1932 in/s^2. Accelerations and forces, F, are related through the objects mass, m, as given by Newton's Second Law: $F = ma$.

Accelerations are of interest in assessing the performance of a vehicle, or to quantify levels of vibration or impact on structures, machines, electronic devices, shipping containers, etc. Accelerations are often used to diagnose the condition of rotating machines, where any increase triggers preventative maintenance prior to catastrophic failure.

11.2 Accelerometers

An accelerometer is an electromechanical device that measures accelerations. Single axis models are common when the direction of acceleration is known. Multi-axis versions are available to detect the complete acceleration vector. Accelerometers are used in air bag systems, video game controllers, and electronic devices to minimize the effect of vibration.

Accelerometer sensitivity, k_a, is typically specified in millivolt per g (mV/g). Therefore, the acceleration can be calculated from the voltage produced by the accelerometer, V_{meter}, as

$$a = \frac{V_{meter}}{k_a} \tag{11.3}$$

The most commonly used accelerometers include:

Piezoelectric Accelerometers

The piezoelectric effect is the ability of some materials, such as crystals and ceramics, to generate an electrical charge when subjected to mechanical stress. Piezoelectric accelerometers use the piezoelectric effect to generate an electrical output that is proportional to applied acceleration. They consist of a mass and piezoelectric component as shown in Fig. 11.1.

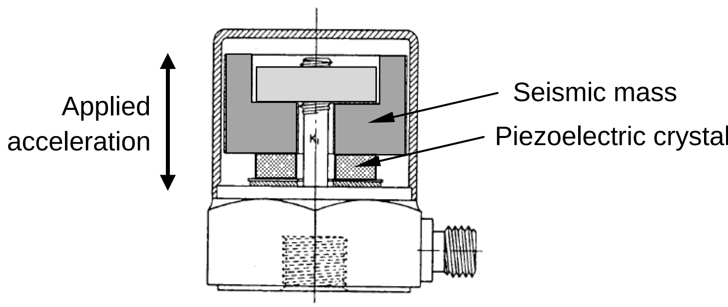


Figure 11.1 Piezoelectric accelerometer

When accelerated, a seismic mass pushes against the piezoelectric component, altering the alignment of positive and negative ions, which results in an accumulation of these charged ions on opposed surfaces. A charge amplifier is used to convert the electrode charge into a voltage. Some accelerometers incorporate charge amplification with internal microelectronics. The PIEZOTRONICS 353B03 requires a charge amplifier and is configured as shown in Fig. 11.2.

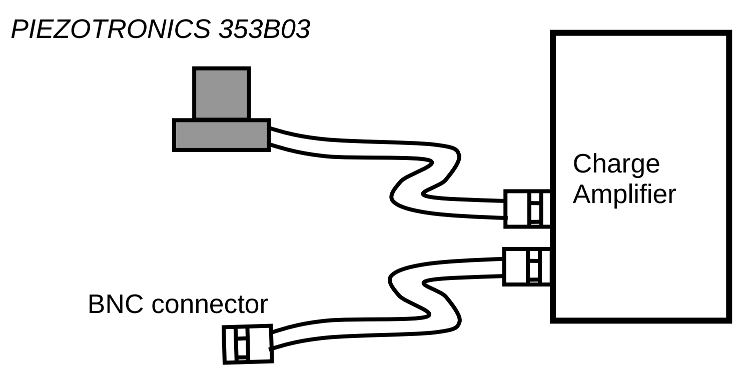


Figure 11.2 Configuring the *PIEZOTRONICS 353B03*

Piezoresistive Accelerometers

A strain gage based accelerometer. A strain gage is placed on a flexible member, supporting a small mass. The strain gage senses the deflection as the mass accelerates. The gages are usually configured in a full Wheatstone bridge. The wire connections and color code are consistent with a typical transducer. Figure 11.3 shows the wire outputs of the *SENSOTEC JTFM/3637*and *KYOWA ASP-100GA* piezoresistive accelerometers.

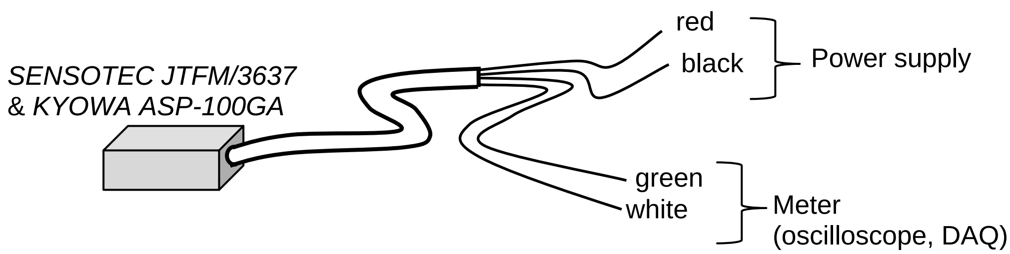


Figure 11.3 Configuring the *SENSOTEC* and *KYOWA* accelerometers

Some piezoresisitve accelerometers are configured as half bridges. In these cases, two external resistors are required to complete the bridge as shown in Fig. 11.4.

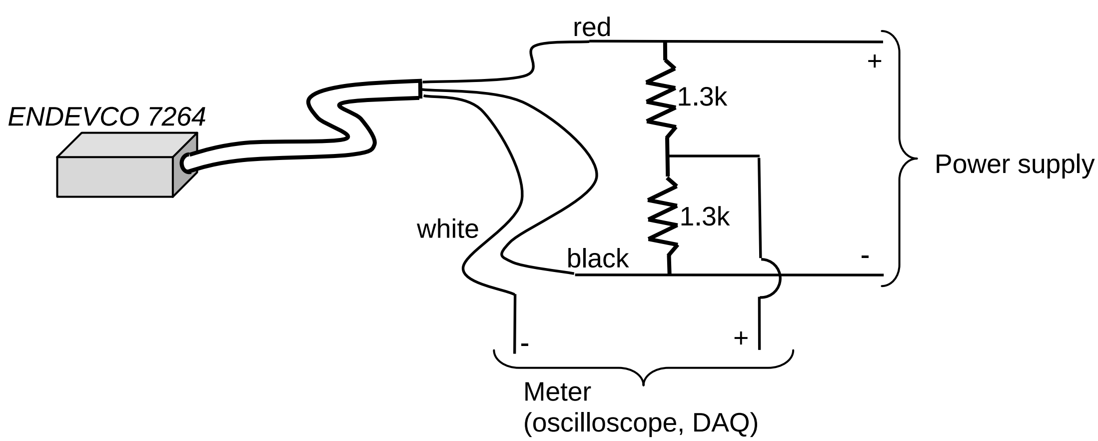


Figure 11.4 Configuring the *ENDEVCO 7264* accelerometer

MEMS Accelerometers

Micro-electrical manufactured systems (MEMS) use a micro-machined structure as a proof mass supported on miniature springs. Deflection of the beam is measured by a differential capacitor and is proportional to the amount of acceleration. The sensor is packaged onto a chip and can be produced at low cost and high volumes. These factors have lead to steady growth into automotive and consumer electronic applications.

11.3 Strain Gages

Strain gages can be used to acquire a dynamic signal, from which the motion characteristics of the structure can be inferred. As an example, a common structural component is a cantilever beam as shown in Fig. 11.5. A cantilever beam is fixed on one end and free on the other. The geometry is specified by a total length, L, and cross sectional properties. In the case of a rectangular beam shown in Fig. 11.5, the base, b, and height, h, are important parameters. The strain gage is mounted a distance d from the free end.

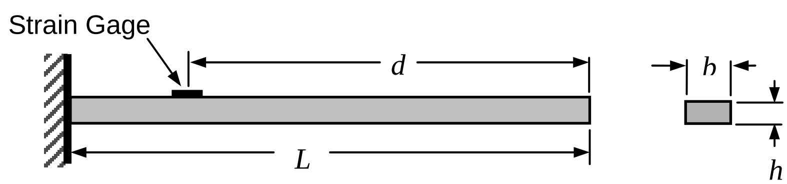


Figure 11.5: Cantilever Beam

The displacement of the free end can be determined from the experimental value of strain, ε, as

$$y = \frac{2L^3}{3d\,h}\varepsilon \qquad (11.4)$$

Since the strain is the only parameter in Eq. 11.4 that varies with time, the velocity and acceleration of the end of the beam can be determined by differentiating the dynamic signal.

$$v = \frac{2L^3}{3d\,h}\left(\frac{d\varepsilon}{dt}\right) \qquad (11.5)$$

$$a = \frac{2L^3}{3d\,h}\left(\frac{d^2\varepsilon}{dt^2}\right) \qquad (11.6)$$

11.4 Vibration

A vibration is the periodic motion of an object displaced from an equilibrium position. The level of vibrations is often measured with accelerometers. The cantilever beam shown in Fig 11.4 is bent, and then released. A plot of the displacement over time appears as a sinusoidal function with a decreasing magnitude. Since the motion is maintained only by gravity and restoring forces, this is classified as a free vibration.

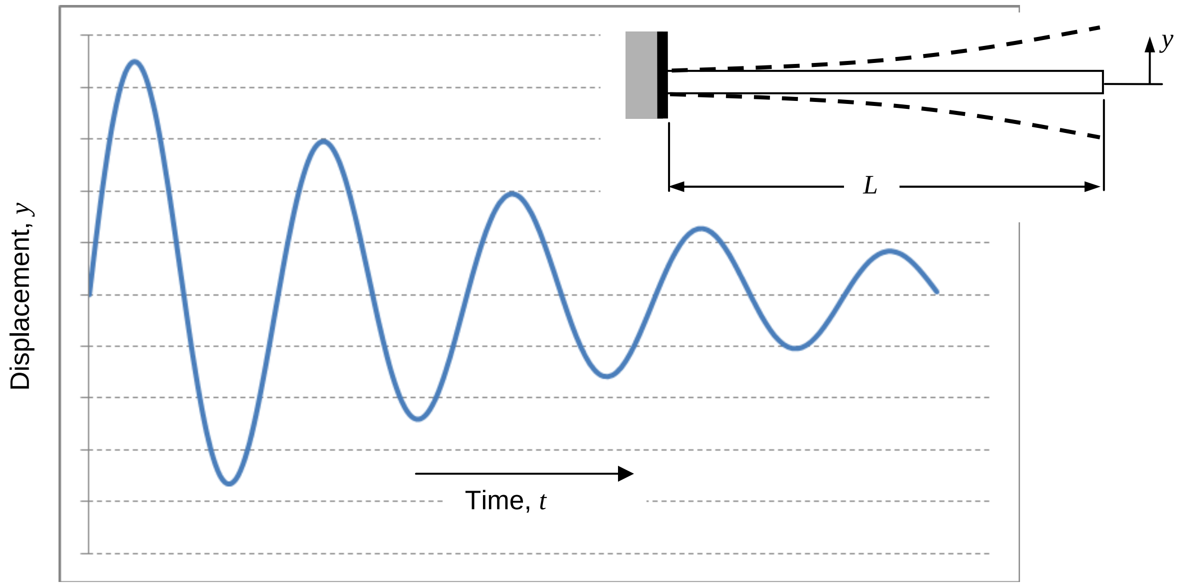


Figure 11.4 Free vibration of a beam

Properties of a vibrating structure are:

a) Frequency, f : the number of vibration cycles that occur per unit time.

b) Period, T : the duration of a single vibration cycle.

c) Amplitude, y_0: the maximum displacement from the equilibrium position.

d) Natural Frequency, f_n: the frequency at which a system will oscillate if there is no outside interference. This is an extremely important attribute of a structure.

e) Damping, c: effects that oppose motion, such as friction or air resistance, that causes the vibration to die out over time.

Free Vibrations

A general equation for the displacement of a point on a structure undergoing free vibration with negligible damping is

$$y = y_0 \sin(2\pi f_n t) \tag{11.7}$$

If damping is considered,

$$y = y_0 e^{-ct} \sin(2\pi f_n t) \tag{11.8}$$

The natural frequency is an inherent property of a structure of system. The identification of the natural frequency is a primary objective, both through equations and testing. Accelerometers or strain gages are commonly used to detect the natural frequency of a structure. The structure may be modified to move the natural frequency and avoid resonance, as will be discussed later.

For a system that resembles a mass, m, supported by springs, with stiffness k, the natural frequency is calculated as

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad (11.9)$$

For the common cantilever beam as shown in Fig. 11.5, the natural frequency is calculated as

$$f_n = \frac{1.75}{\pi L^2}\sqrt{\frac{EI}{z}} \qquad (11.10)$$

where:

Section moment of inertia, $I = \frac{bh^3}{12}$

Mass per unit length, $z = \frac{\rho bh}{386.4\,\text{in/s}^2}$

Density, ρ = 0.283 lb/in^3 (steel) = 0.100 lb/in^3 (aluminum)

Forced Vibrations

A forced vibration occurs when an external force is repeatedly applied to the system, such as an unbalanced motor or engine. The forced vibration is excited with an amplitude, F_0, at a forcing frequency, ω, specified in revolutions per second.

In the case of an unbalanced motor with an eccentric weight, W, offset from the center of rotation by a radius, r, the force amplitude is calculated as

$$F_0 = \frac{Wr(2\pi\omega)^2}{386.4\,\text{in/s}^2}\ \text{lbs} \qquad (11.11)$$

The steady-state magnitude of a forced vibration is

$$y_{ss} = \frac{(F_0/k)}{\sqrt{\left[1-(\omega/f_n)^2\right]^2 + \left[2\xi(\omega/f_n)\right]^2}} \qquad (11.12)$$

where:

Stiffness, $k = \frac{3EI}{L^3}$ (for a cantilever beam)

Damping ratio, $\xi \approx 0.1\ \text{to}\ 0.3$ (for typical mechanical structures)

Frequency Response

Resonance is the tendency for an object under a forced vibration to oscillate at larger frequencies than others. It occurs when a structure is excited at its natural frequency. A common plot is the vibration amplitude as a function of the forced vibration frequency. The resonance, along with the magnification at different forcing frequencies becomes clearly recognizable. An example of a frequency response plot is shown in Fig. 11.7.

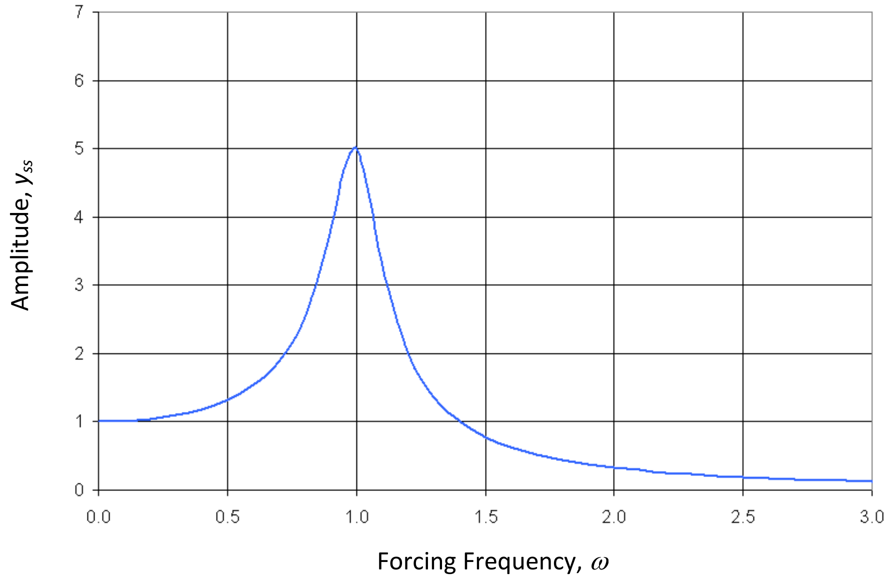


Figure 11.7: Frequency Response Plot

Pre-Lab Exercises:

10-1. A package is dropped from 5 ft and reaches a speed of 18 ft/s. It crashes onto a concrete floor and comes to rest in 0.012 sec. Determine the acceleration level during the impact in ft/s^2 and g's.

10-2. The displacement of a point is given as

$$y = 0.75 \sin(10t)$$

Determine an equation for the acceleration of the point.

10-3. A periodic signal with a peak-to-peak voltage of 0.78 V is produced by an accelerometer with a sensitivity of 10 mV/g. Determine the maximum acceleration.

Laboratory Experiences:

10-1. Determine the accuracy of natural frequency measurements.
- a) Use a large C-clamp to fixture a cantilever beam.
- b) Write a LabVIEW program to capture a finite waveform and use spectral analysis to measure the dominant frequency.
- c) Use LabVIEW to measure the natural frequency of the beam from a:
  - i. strain gage (signal conditioned).
  - ii. piezoelectric.
  - iii. piezoresistive (signal conditioned)
- d) Repeat measurements at several (at least 6) other cantilever lengths.
- e) Calculate the theoretical natural frequency for the different lengths used.

f) Observe accuracy tendencies and trends for vibration frequency measurements.
g) As always, assist in the lab cleanup.

10-2. Determine the characteristics of a frequency response plot of a cantilever beam.
a) Use a large C-clamp to fixture a cantilever beam. Sandwich the beam between a few rubber pads and steel blocks.
b) Attach a motor, with an offset weight to the free end of the beam.
c) Construct a circuit that will allow the motor to be driven from LabVIEW.
d) Attach a piezoelectric accelerometer to the beam and send the signal into a DAQ channel.
e) Twang the beam and use the accelerometer to determine its natural frequency.
f) Write a LabVIEW program to:
   i. Capture 2 seconds of the sensor signal
   ii. Use the tone function to measure the dominant frequency and its associated amplitude.
   iii. Automatically write this information into a file.
g) In two second intervals, gradually increase the power supply voltage to the motor.
h) Convert the sensor signal voltage to displacement amplitude at the end of the beam.
i) Create a frequency response graph.
j) Calculate the theoretical vibration amplitude.
k) Comment on trends encountered.
l) As always, assist in the lab cleanup.

Chapter

12

ANALOG OUTPUT

12.1 Analog Output

In addition to acquiring voltages, most data acquisition (DAQ) boards can also be configured to supply a voltage. These are called analog outputs (AO). The DAQ equipment located in the lab (NI-USB-6221 & BNC-2120) are equipped with two AO channels. AOs are configured similarly to AIs, as shown in Fig. 12.1 and 12.2.

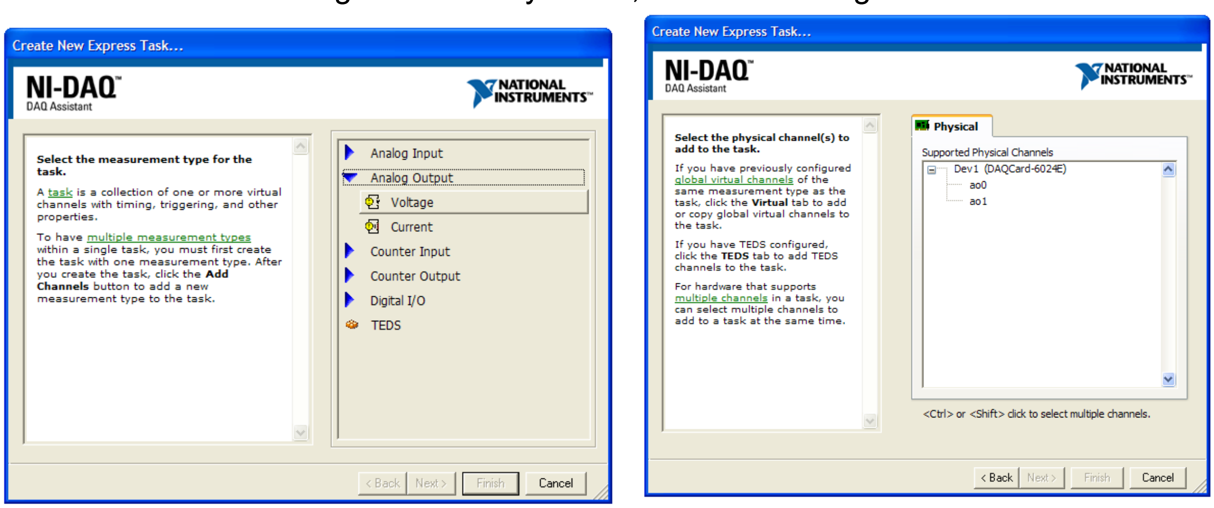


Figure 12.1 Setting up an AO Channel

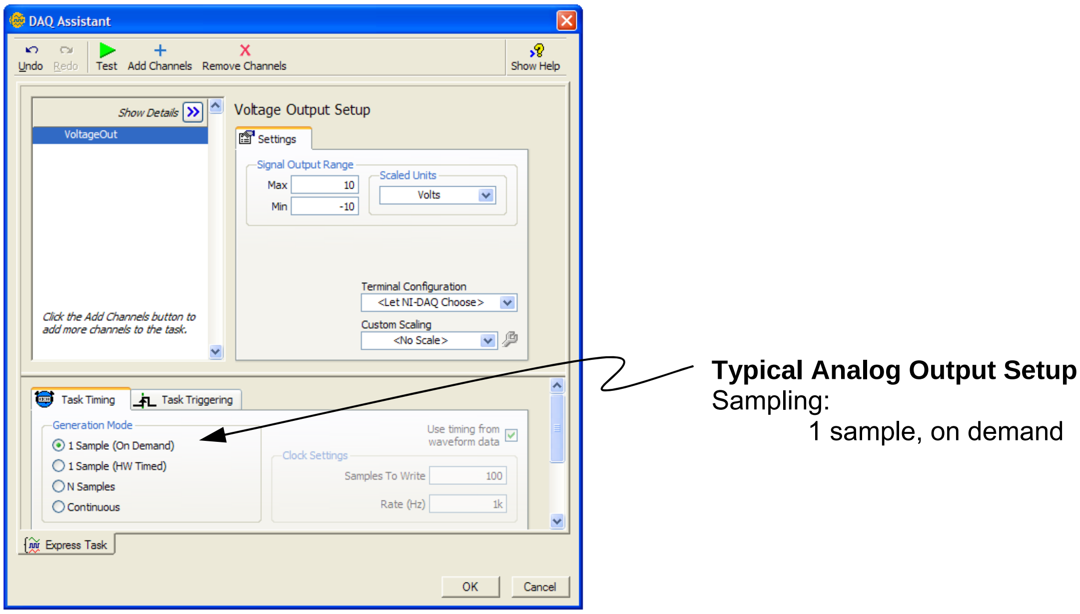


Figure 12.2 Configuring an AO Channel

A simple LabVIEW program to supply a voltage to an AO is shown in Fig. 12.3.

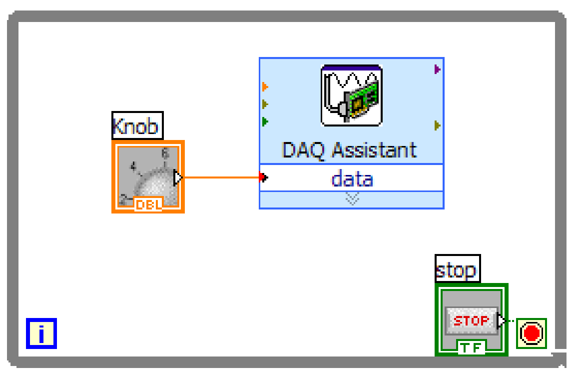
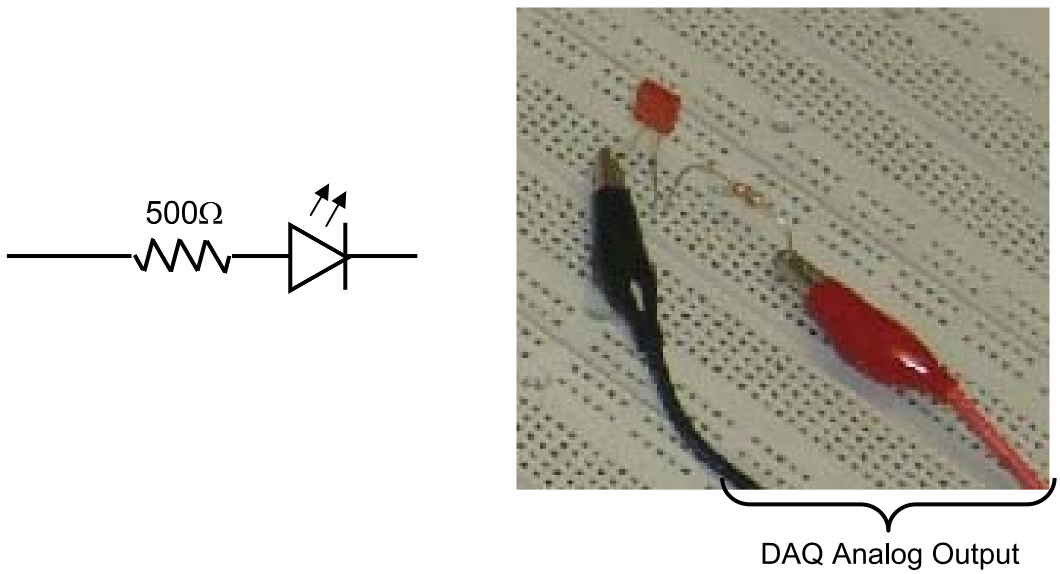


Figure 12.3 LabView Program to supply a voltage

12.2 Operating LED's from DAQ

A DAQ board can directly operate low power devices, such as light emitting diodes (LEDs). An LED requires a certain amperage to operate, but does not possess a resistance. Therefore, a resistor must be placed in the circuit to limit the current. For example, to provide a 20 mA to an LED, when supplying 10V from the DAQ AO, a 500Ω resistor should be used as shown in Fig. 12.4.

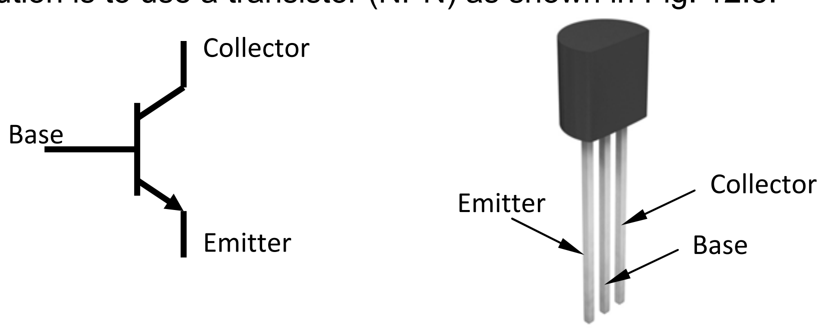


(a) (b)

Figure 12.4 Powering an LED from the DAQ AO

12.3 Driving a High Amperage Load from DAQ

The DAQ equipment in the lab can only supply low amperage (<20 mA). High load actuators, such as motors, require more amperage than control devices can supply.
A common solution is to use a transistor (NPN) as shown in Fig. 12.5.



(a) Symbol (b) TO-92 Package

Figure 12.5 NPN Transistor

The transistor can be configured to act as a switch. As small control current, coming from the voltage supplied by the control device (such as DAQ) flows into the base the transistor is “turned on”. A much larger current is allowed to flow from the collector to the emitter. Thus, a motor can be driven from a small amperage source (such as the DAQ system) using the transistor circuit shown in Fig. 12.6.

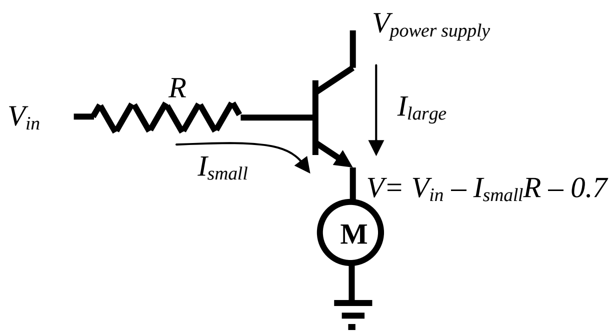


Figure 12.6 Transistor Switch Circuit

If the current required of the load is substantial (>100 mA) then a power transistor should be used. A common power transistor is the TIP47, which can carry a continuous collector current of 1.0A. The pin arrangement of the TIP 47 is shown in Fig. 12.7.

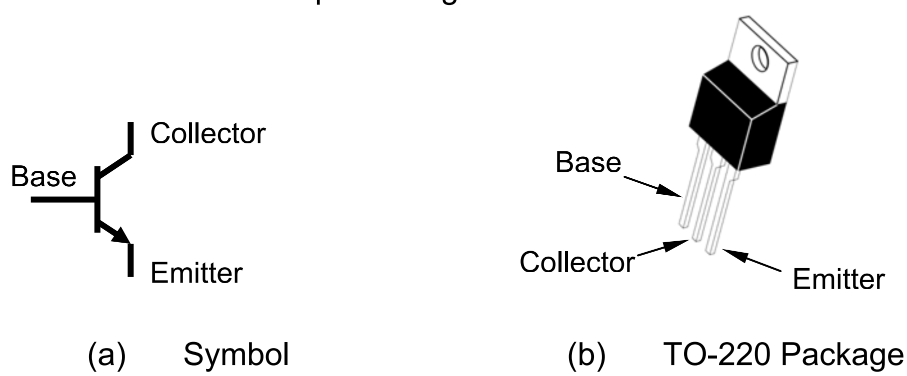


Figure 12.7 TIP47 NPN Power Transistor

12.4 Driving a Motor from DAQ

To drive the motor from DAQ, an NPN transistor circuit shown in Fig 12.8 should be used. The 500Ω resistor is to limit the amperage draw from the DAQ.

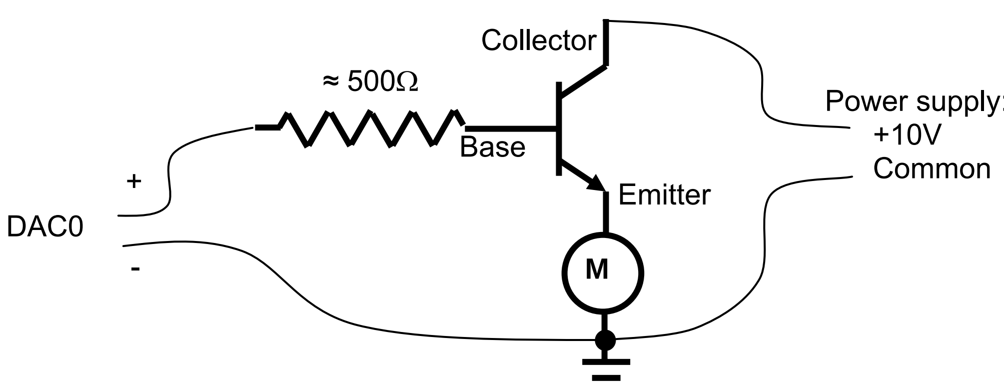


Figure 12.8 Motor Drive Circuit

The physical circuit is shown in Fig 12.9.

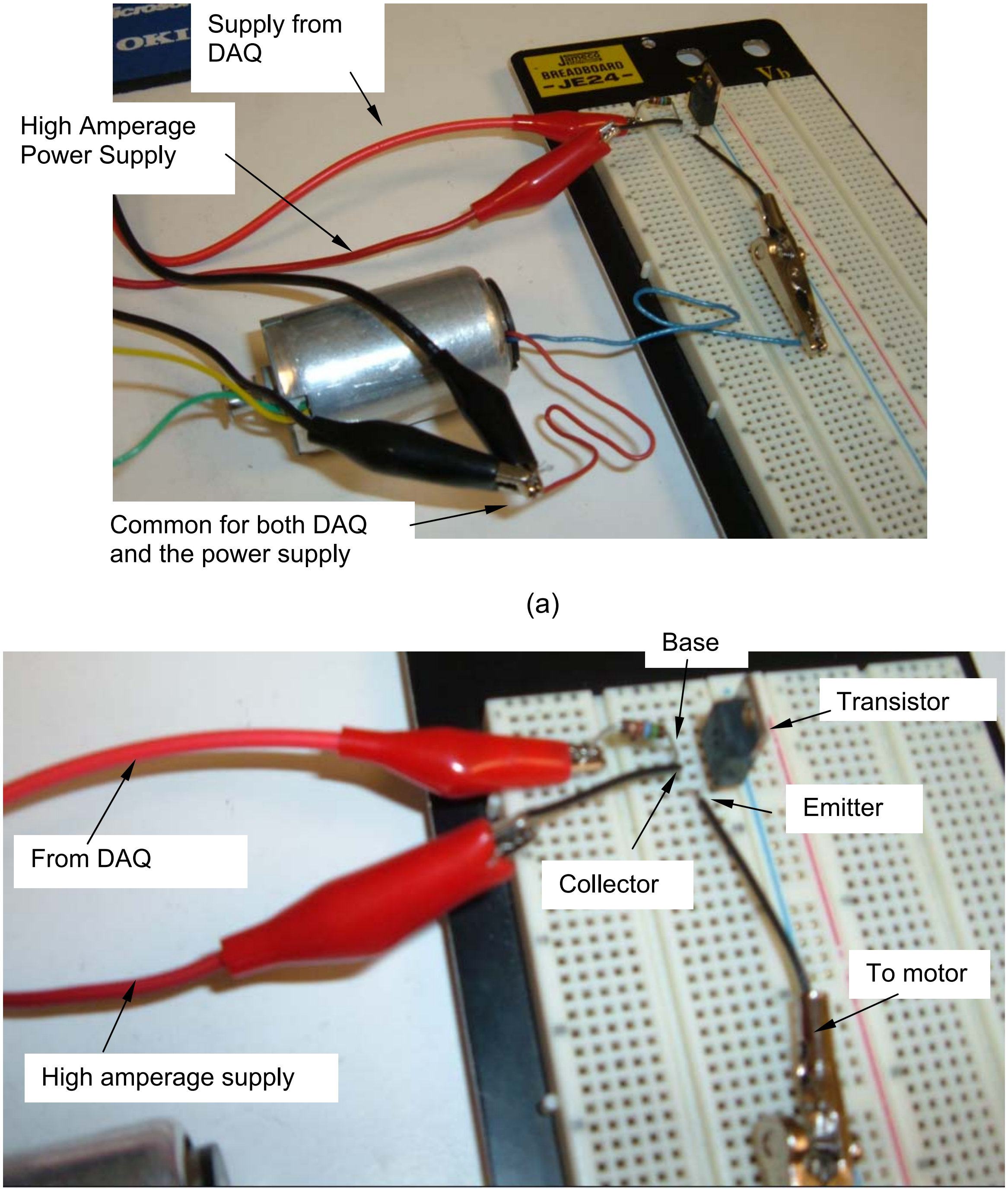


Figure 12.9 Physical Motor Drive Circuit

Pre-Lab Exercises:

12-1. An LED requires 15 mA to achieve the desired intensity. A 5V analog output will be used to illuminate the LED. Determine an appropriate current limiting resistor for this application.

12-2. The TIP47 transistor has a current gain of 30, meaning that 1/30 of the emitter current comes through the base. A motor requires 0.5A to operate at 10V with no load. If that motor is actuated from DAQ in a manner shown in Fig. 12.8, determine the current draw from DAQ.

Laboratory Experiences:

12-1. Determine the motor speed constant with LabVIEW altering the speed of a motor by adjusting a knob, and collecting the data measurements.

a) Create a circuit to drive a motor from a low amperage source, such as DAQ.
b) Create a LabVIEW program to use a knob to send a voltage to the motor drive circuit. **Be extremely careful!!! Do not send any voltage into the analog output. This will destroy the $1500 DAQ board.**
c) Run the program and adjust the speed by turning the knob in LabVIEW.
d) Alter the LabVIEW program so that it acquires the voltage actually being sent to the motor and the tachometer frequency (green and yellow wires). Display the motor speed in rpm. There are eight tachometer pulses per revolution.
e) Run the program and verify that the motor voltage and speed are being displayed.
f) Create a LED circuit.
g) Alter the LABVIEW program so that an LED is lit when the motor speed exceeds or falls below set limits.
h) Run the program. Adjust the knob and record the rpm and motor voltage.
i) Repeat at several other knob settings.
j) Create a graph of voltage vs. motor speed, and calculate the slope (rpm/V).
k) As always, return all equipment and cleanup your lab bench.

Chapter

13

INTRODUCTION TO CONTROL

13.1 Open-loop Control

Open-loop control, is also called non-feedback control, and is a manner of operating a system by using a predictive model. For example, an irrigation sprinkler system programmed to turn on at set times is open-loop system. A model predicts that a lawn would flourish if it is watered every morning for 20 minutes. Even when sufficient rain is available, the sprinkler system would activate on schedule.

In control terminology, the physical system is called the plant and the conversion software/hardware is the controller. A schematic of an open-loop control system is shown in Fig. 13.1.

Figure 13.1 Schematic of Open-loop Control

Open-loop control is suitable for well-defined systems where the relationship between input and the resultant state is predictable and can be mathematically modeled. For example, controlling the speed of a dc electric motor that drives a constant load is a good application of open-loop control. The motor voltage and resulting speed adhere to a well-defined, linear relationship.

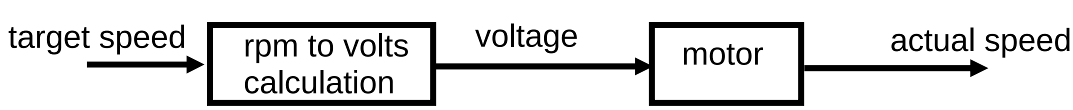


Figure 13.2 Open-loop Control of Motor Speed

If the load was not predictable, the motor speed would vary as a function of the load as well as of the voltage, and an open-loop controller would not accurately control the velocity. Open-loop control is used in simple processes because of its simplicity and low-cost.

13.2 Closed-loop Control

To obtain a more accurate or more adaptive control, a sensor monitors the output of the system and provides a command to the controller. This type of system is called a closed-loop system. For the irrigation system mentioned above, a system that measure soil moisture to determine the level of watering necessary would be much more accurate. Consequently, it would also be more complex and expensive.

Figure 13.3 shows a simple on/off temperate control LabVIEW program. It turns a heater on and off based on a comparison of the temperature measurement and the set-point. If the set-point is higher, a positive signal is sent to the heater. Otherwise, no signal (zero) is sent to the heater.

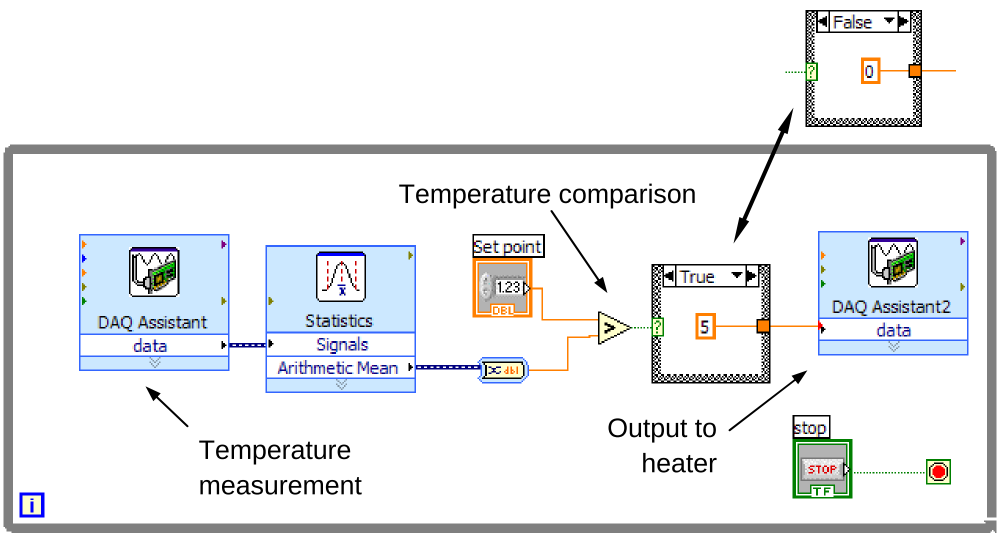


Figure 13.3 Closed-loop, On/off Temperature Control

Notice, that the temperature controller in Fig. 13.3 will short cycle. That is, the heater will continually fluctuate between on and off as the temperature hovers around the set point. This control is detrimental to the mechanical components of the heater/fan.

A more elaborate program would eliminate short cycling by setting a temperature where the heater would turn on, and a higher temperature, where the heater would turn off. An example of such a program is shown in Fig. 13.5. A differential is supplied to define a range for the acceptable temperatures. A shift register is used to track whether the heater is off. If the temperature exceeds the maximum, the heater is turned off. If the temperature is within the range and the heater is already on, the heater will stay on. When the temperature falls below the minimum, the heater turns on.

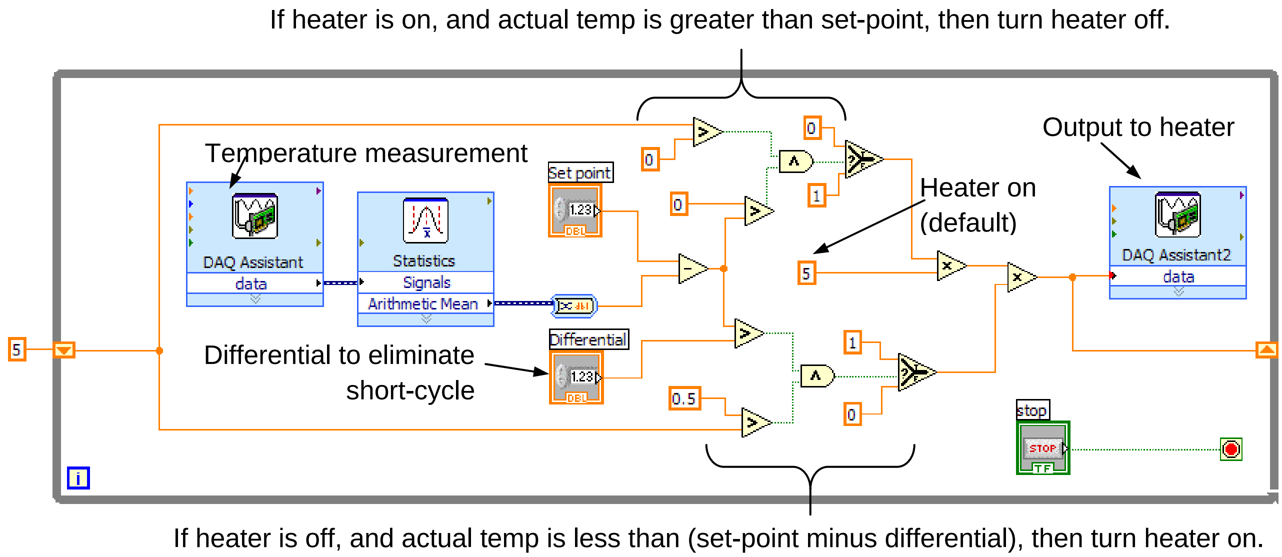


Figure 13.4 Closed-loop, On/off Temperature Control

13.3 Continuous Feedback Control

In continuous feedback control, a sensor monitors the output of the plant and feeds the data to a processor which continuously adjusts the control input to keep the error to a minimum. Feedback on how the system is actually performing allows the controller to dynamically compensate for disturbances to the system. An ideal feedback control system cancels out all errors, effectively mitigating the effects of any forces that may or may not arise during operation and producing a response in the system that perfectly matches expectations.

A classic example of feedback control is the cruise control in an automobile. A sensor monitors the vehicle speed, sending a signal to the onboard computer which continually adjusts the throttle to maintain the desired speed. The feedback allows the speed remain steady even as conditions, such as slope of the terrain and wind speed, change. A schematic of continuous feedback control system is shown in Fig. 13.5

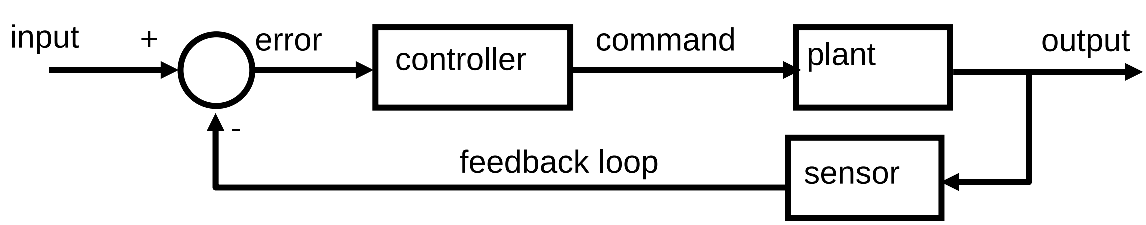


Figure 13.5 Schematic of Continuous Feedback Control System

In the case of controlling motor speed, a closed-loop controller would measure the actual rpm with a sensor. The difference (error) between the target and actual rpm is determined. The motor speed is automatically controlled by continually adjusting the voltage supplied to the motor in proportion to the error. Since the adjustment is proportional to the error, this control strategy is called proportional control.

The controller regulates the control voltage in an attempt to adjust the motor speed. A test must be run to determine the relationship between the control voltage and motor speed.

13.4 Feedback Gain

Gain can be added to a control system to assign greater influence on the feedback. As an example, imagine turning the water on when taking a shower. If the water is too cold, you turn on more hot water. The quickness of your decision to adjust the water valves is similar to feedback gain. If the gain is set at a high value, the response may be an over - reaction. The difference between a high and low gain control system is illustrated in Fig. 13.6.

The performance of a closed-loop control system is primarily assessed based on the overshoot, setting time, long term error. These assessment parameters are shown in Fig 13.6.

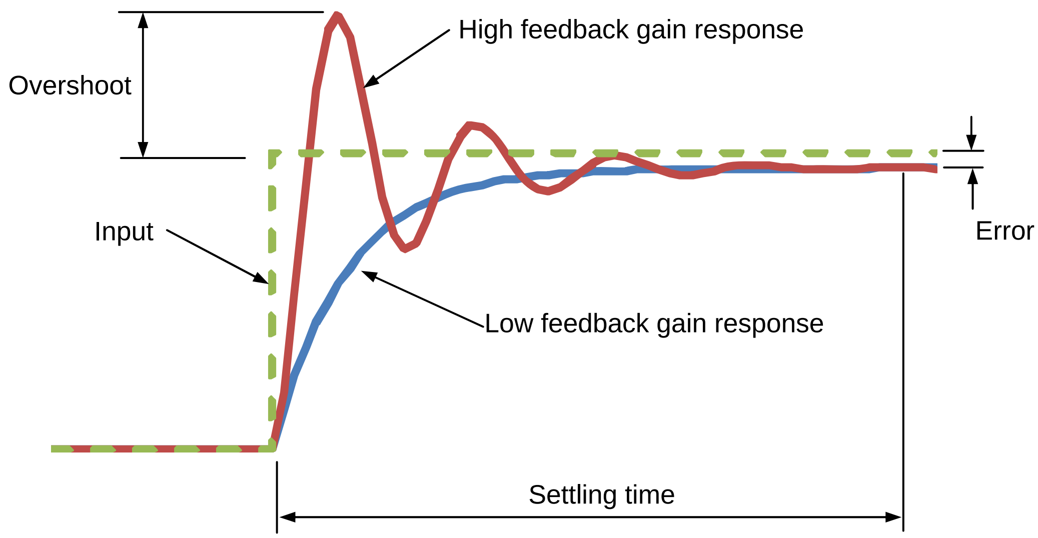


Figure 13.6 Characteristic Response of Closed-loop Control

13.5 LabVIEW Feedback Control Program

A LabVIEW program that controls the speed of a motor should:

a) Provide an initial voltage to the control program.
b) The error between the measured rpm and the target rpm should be calculated.

c) A voltage adjustment should be calculated in proportion to the rpm error.
d) The voltage adjustment must be combined with the previous voltage and sent to the next loop iteration (as a shift register).

Figure 13.7 shows a LabVIEW motor speed control program. The program adjusts the voltage supplied to the motor based on the error between the measured speed and the target speed. Notice that an open-loop conversion factor of 412.5 rpm per volt has been predetermined. This program will continually adjust the speed of the motor if the target speed is changed, or if the load on the motor is altered.

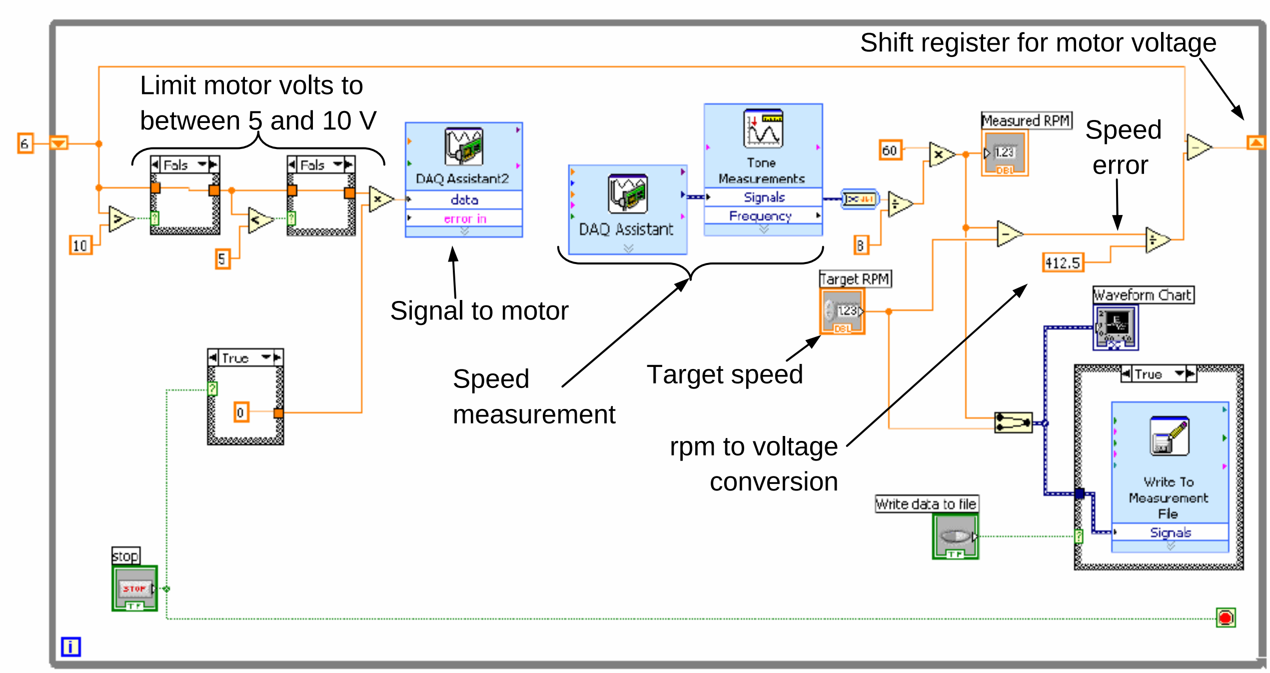
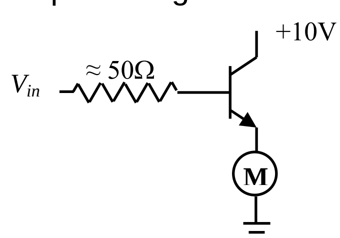


Figure 13.7 Motor Speed Control Program

Pre-Lab Exercises:

13-1. As 4 V is applied to the motor control circuit, the motor rotates at 1000 rpm. As 10 V is applied as input, the motor rotates at 3475 rpm. Determine the relationship between the input voltage and the motor speed.



13-2. For the motor control circuit above, the target speed is set at 2000 rpm. Currently, 6 V is fed to the circuit and the speed is 2450 rpm. Determine the adjustment that should be made to the motor control voltage.

Laboratory Experiences:

13-1. Quantify the performance of a program that will control speed of a motor.

a) Determine the motor speed to control voltage relationship for the motor under test (there are 8 pulses per revolution)
b) Design and implement a LabVIEW program to control the speed of a motor:
    i. Reads the actual motor speed from the tachometer (rpm)
    ii. Compares actual motor speed to a target motor speed and creates a speed error
    iii. Calculates an adjusted voltage that is proportional to the speed error
    iv. Multiplies the voltage adjustment by a gain to adjust the impact of the controlling action
    v. Sends the modified control voltage to an analog output channel to drive the motor
    vi. Be careful, the control voltage must not exceed the limits of the analog channel
    vii. Turns the motor off using a “Stop” button
    viii. Provides a means to record the control action driving the motor
c) Clearly document, and fully understand how the program operates
d) Develop a testing method to analyze the performance of the control system and to evaluate the effects of gain on the control action
e) Determine parameter(s) that can be used to quantify the performance of your control system and how they can be measured
f) Analyze any trends noticed and comment on the best control action for various motor applications
g) As always, return all equipment and cleanup your lab bench.

13-2. To determine the performance of a program that will control the speed and temperature of a motor.

a) Determine the motor tachometer output (pulses per cycle) of the given DC motor.
b) Determine the relationship between the motor speed and the control voltage.
c) Design and implement a LabVIEW program to control the speed of a motor:
    - Reads the actual motor speed from the tachometer (rpm)
    - Compares actual motor speed to a target motor speed and creates a speed error
    - Calculates an adjusted voltage that is proportional to the speed error
    - Multiplies the voltage adjustment by a gain to adjust the impact of the controlling action
    - Sends the modified control voltage to an analog output channel to drive the motor
        - Be careful, the control voltage must not exceed the limits of the analog channel
        - Turns the motor off using a “Stop” button
    - Provides a means to record the control action driving the motor

d) Add to this LabVIEW program the ability to cool the motor drive transistor if necessary:
   - Monitor the temperature of the motor drive transistor.
   - Turn a fan on that cools the transistor if the temperature becomes greater than a specified set-point.
   - Turn the fan off is the temperature is 10 ^{0}F lower than the set-point.

e) Develop a testing method to analyze the performance of the control system and to evaluate the effects of gain on the control action
   - Determine parameter(s) that can be used to quantify the performance of your control system and how they can be measured
   - Analyze any trends noticed and comment on the best control action for various motor applications

f) As always, return all equipment and cleanup your lab bench.