# CHAPTER 10
## SYSTEM-LEVEL CONSIDERATIONS

*An Amazingly Brief History of Measurement*

In the past, measurement was most often based on the length of a ruler's arm, or foot, or hand. The word "ruler" is still used to refer to a standard length.

The lack of standards for weights and measures was long used by the unscrupulous to dupe the unwitting. In France prior to the revolution, the saying *"un roi, une loi, un poids, et une mesure"* (one king, one law, one weight, and one measure) was often heard. In 1790, the French National Assembly directed the French Academy of Sciences to develop a model for weights and measures.

The resulting standardization of weights and measures in France during 1795 was the culmination of efforts that began under Charlemagne. The Academy's recommendation included the metric system with its stipulation that multiples of all basic units be in factors of 10.

The U.S. Constitution gives congress the authority to maintaining systems of weights and measures.

In 1821, John Quincy Adams, in a report to congress, stated the necessity for any society to maintain a system of weights and measures. In 1832, the U.S. Treasury Department introduced a system of weights and measures. In 1836, the US Congress approved these standards.

In 1875, the U.S. and 16 other countries signed the "Treaty of the Meter" establishing a central bureau of standards in France.

The National Institute of Standards and Technology was established by act of Congress on Mar. 3, 1901. It was known as the National Bureau of Standards until 1988. Uniformity in measurement is maintained by regular international meetings.

> "To measure is to know." *Lord Kelvin*

> "When you measure what you are speaking about and express it in numbers, you know something about it, but when you cannot express it in numbers your knowledge about is of a meagre and unsatisfactory kind." *Lord Kelvin*

> "Every item of physical knowledge must therefore be an assertion of what has been or would be the result of carrying out a specified observational procedure." *Sir Arthur Eddington*

> "Metric is definitely communist. One monetary system, one language, one weight and measurement system, one world - all communist! We know the West was won by the inch, foot, yard, and mile." *Dean Krakel, Director of the National Cowboy Hall of Fame*

> "Weigh and Pay." *Adam Smith, in The Wealth of Nations*

## 10.1 Introduction

The emphasis in this chapter will be on the measurement task from an overall perspective—from sensing a physical quantity with a sensor through the acquisition of measurement data in electronic form for control and/or for modeling and analysis. An extended example will be employed to illustrate a specific measurement task. The rest of the chapter will be used to explore potential constraints and possible problems that must be considered for the system to function adequately.

Considerations include the proper use of sensors—the point being that an engineer should develop a thorough understanding of the sensor being employed. Once the signal is in electrical form, it is often necessary to use signal conditioning for filtering, amplification, biasing, and overvoltage protection. An understanding of coupling mechanisms for electromagnetic interference (EMI) allows the designer to better effects their effects. If the data is to be used for modeling or analysis, an analog-to-digital converter can be used to obtain digital data, which then can be analyzed and displayed by programs such as MATLAB or Microsoft Excel.

## 10.2 An Extended Example

The system below shows a system where temperatures in metal processing are to be measured and recorded. In the diagram, the sensor output is assumed to be a voltage which is amplified by the non-inverting op-amp amplifier. The amplified analog signal (the voltage $V_o$) is then converted to digital form which can be readily manipulated using analysis or modeling software.

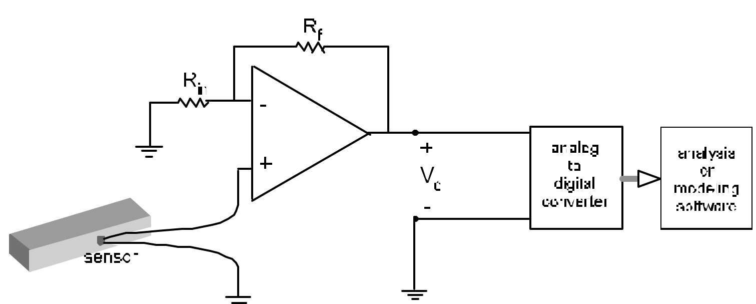


**Figure 10.1: Temperature Measurement System**

Where to start and will it work? Engineers address these questions in any system design. Here the sensor will be considered first. Whether a measurement system will function adequately depends upon the sensor's appropriateness to the task, on the presence of noise, which can affect the accuracy of the measurement, on the presence of overvoltages which may cause the system to malfunction, and on the speed and resolution of the analog-to-digital converter (ADC).

To be more specific, assume the application is in metal processing, with harsh environments including high temperatures as well as high electric and magnetic fields.

Assume the temperatures to be measured are high, above 400 °C, with a maximum temperature of 1600 °C. Particular care should be taken to ensure the system is not affected by the fields produced by the large AC voltages and currents present.

### 10.2.1 *Sensor Characteristics*

To begin with, the selection of sensor, particular attention must be paid to the high temperature being measured. Neither a thermistor nor an RTD would be appropriate sensors to measure these high temperatures. Two possible options would be to use non-contact optical measurements or to use a thermocouple.

Non-contact optical measurements are increasingly being used in measurement. Optical temperature measurements typically are based on the fact a given body will emit electromagnetic radiation (for the purposes here in the infrared and visible) with a certain spectrum and intensity, both of which vary with temperature. There are several existing schemes for relating the intensity and spectral characteristics of the emitting body to the temperature. Optical techniques are immune to electromagnetic interference and can be used in applications involving hazardous locations involving the presence of volatile and flammable gases without the need for expensive explosion-proof enclosures required when using electrical systems.

A temperature sensor that would have widespread application in this case would be the thermocouple. Supposing, in fact, that a thermocouple has been chosen, do the high temperatures being measured place restrictions on the type of thermocouple? An investigation of this question would reveal that platinum-rhodium (type B or S, for example) thermocouples would have sufficient ranges. There are tungsten-rhenium thermouples that can measure temperatures over 2500 °C, but, at high temperatures, they must be contained in a vacuum or inert atmosphere to avoid oxidation. Choosing type B, which has a range of over 1800 °C, the next question would be about how to connect and use the sensor.

Temperature measurement with thermocouples typically involves two thermocouples. One, the sensing junction, is at the temperature being measured and the second, the reference junction, is at a known temperature. Thermocouple tables assume the reference junction is at 0 °C.

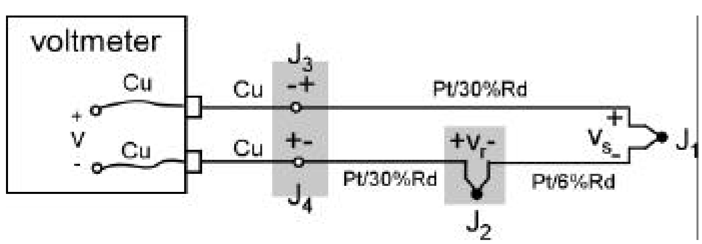


**Figure 10.2: Thermocouple Temperature Measurement**

Type B thermocouples are formed by joining Pt/30%Rd, the positive lead, to Pt/6%Rd, the negative lead. There are thermally EMFs generated whenever two dissimilar metals are joined. In Fig. 10.2 there are two intentional Type B junctions, $J_1$ and $J_2$, and two unintentional junctions, $J_3$ and $J_4$. Note that, if the temperature at $J_3$ and $J_4$ are the same their thermal EMFs will cancel. This can readily be accomplished by locating them at the voltmeter.

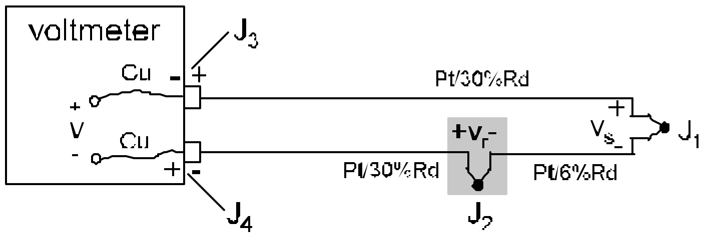


**Figure 10.2: Thermocouple Temperature Measurement**

The voltage at the voltmeter, $V = V_s + V_r$, is the sum of the voltage at the sensing junction, $J_1$, and the reference junction, $J_2$. Thermocouple tables and curves assume the reference junction is at 0°C. Therefore, strictly speaking, one would use the setup shown in Fig. 10.2, with $J_2$ held at 0°C.

This might not be necessary in this case because of the very high temperatures being measured at $J_1$. The difference between $V_r$ at 0°C and $V_r$ at a normal room temperature of 25°C is just 3 μV. When $J_1$ is at 400 °C, V = 0.787 mV (assuming $J_2$ at 0°C) so that an error of less that 0.5% would result if the reference junction were allowed to be at room temperature. The system would remain fairly accurate even if the reference junction was allowed to be at room temperature.

The Type B thermocouple is peculiar in one respect—it is double valued. Its voltage is zero at both 0°C and at 42°C as shown in Fig. 10.3 (that is, $V = V_s + V_r = 0$ for $J_1$ at 0°C or 42°C assuming $J_2$ is being held at 0°C). This characteristic makes the Type B thermocouple useless at low temperatures.

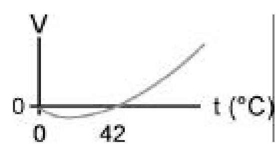


**Figure 10.3: Type B Voltages at Low Temperatures**

Note that this measurement system has been designed to function at high temperatures. It would not serve as well at low temperatures due to the relatively low voltages produced by the Type B thermocouples (Type B thermocouples are not as sensitive as other thermocouple but are able to function at the high temperatures required in this application). If the system were designed to measure lower temperatures, other types of thermocouples would be better choices. Type B is a good choice here since these other thermocouples (perhaps Type K or N) which have higher thermal EMFs simply cannot withstand these high temperatures.

### 10.2.2 *Signal Conditioning*

Is the signal conditioning shown in Fig. 10.1 adequate? For this discussion, assume the ADC input voltage range is 0-5 V.

Requirements can be found by beginning with the characteristics of the sensor and the particular application. Thermocouples provide voltages in the millivolt range and cannot provide much current. The nature of the application ensures the signal will vary only slowly with time. The harsh environment allows the possibility of noise and the need for overvoltage protection.

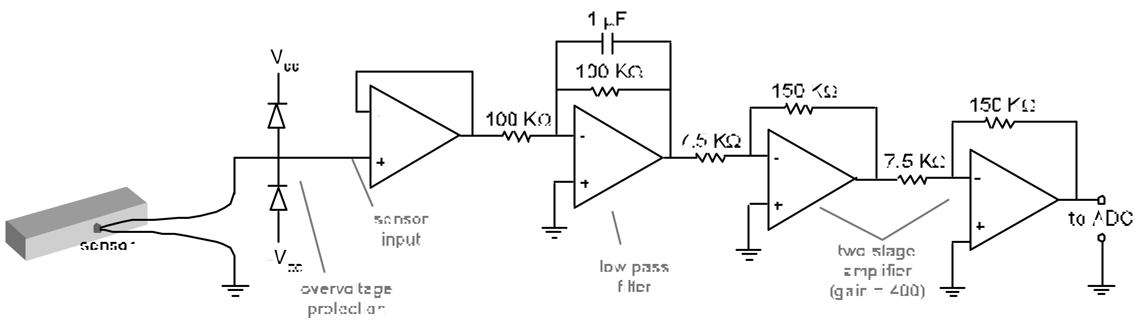


**Figure 10.4: Signal Conditioning – First Try**

Overvoltage protection is provided by two diodes which limit the input voltage to approximately ±($V_{cc}$ + 0.7 V). The sensor is fed into a voltage follower input, which requires very little current as demanded by the sensor type. The low pass filter has a break frequency of 10 r/s so that even 60 Hz noise from the power system is attenuated. The amplification section allows the sensor output of 11 mV at 1600 °C to be scaled to 4.4 V for the ADC input.

The system shown in Fig. 10.4 could allow noise to enter the system through the connection of the sensor to ground (for discussion of noise coupling see section 10.3). Feeding the sensor into a differential input could help reduce this noise.

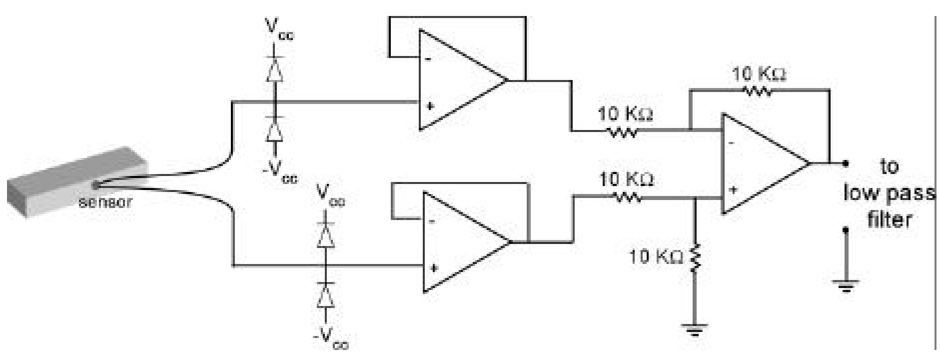


**Figure 10.5: Improved Sensor Input**

**Note:** Many times, particularly in industrial applications, a 4-20 mA transmitter would be used as a component in signal conditioning. Transmitters, designed to convert the TC output into a 4-20 mA current signal, are readily available from a variety of manufacturers. They can be modeled as dependent sources, as voltage-controlled current sources (VCCS). The TC signal, a voltage, is converted to a current using the transmitter which, therefore acts as a VCCS.

Using a 4-20 mA loop could help reduce noise at the differential input. Using a 250 Ω resistor in the 4-20 mA loop, as shown in Fig. 10.6, could serve to convert the signal to 1-5 V, suitable for the ADC. As can be seen, using a 4-20 mA loop, would also serve to eliminate the need for further amplification.

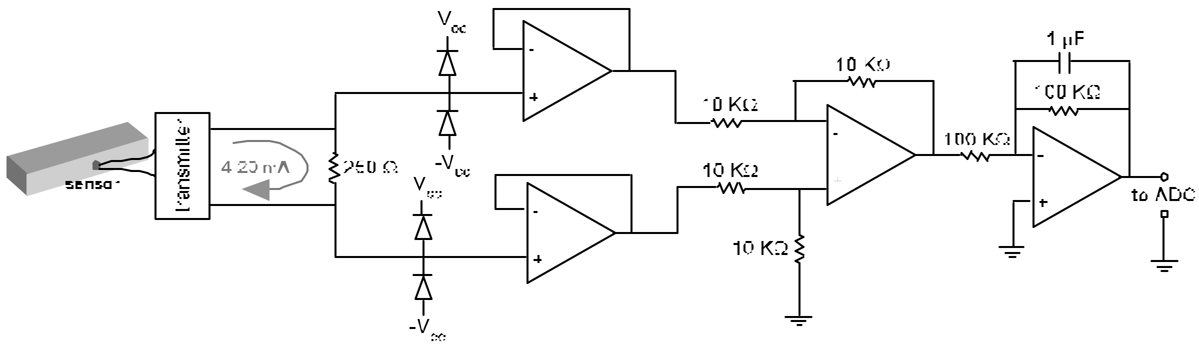


**Figure 10.6: Using a 4-20 mA Transmitter**

Using a 4-20 mA loop will not be considered further in this chapter.

### 10.2.3 *Additional Noise Mitigation Techniques*

In section 10.2.2, not including the discussion of using a 4-20 mA loop, two steps were taken to control noise—the first was to use a low-pass filter and the other was to use a differential input.

Additional steps such as using an electrostatic shield, using twisted pair wires to connect the thermocouple sensor to the signal conditioning system would serve to reduce further the risk of noise interfering with the measurement of temperature.

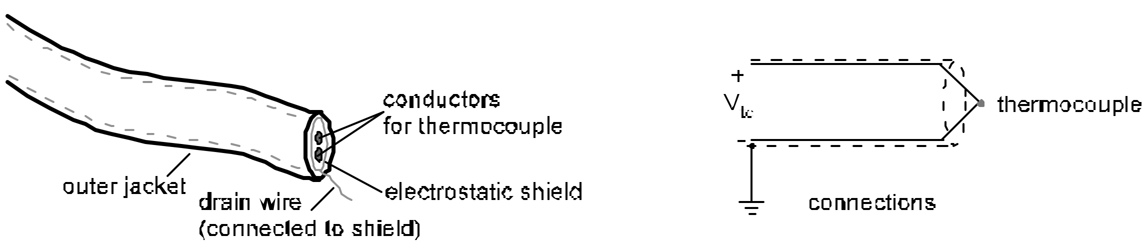


**Figure 10.7: Single Pair Cable with Electrostatic Shield Connections**

In fact, most thermocouple extension cable has an electrostatic shield in which each pair of conductors is twisted (why electrostatic shields are useful and how twisted pair wiring can reduce noise is discussed further in section 10.3).

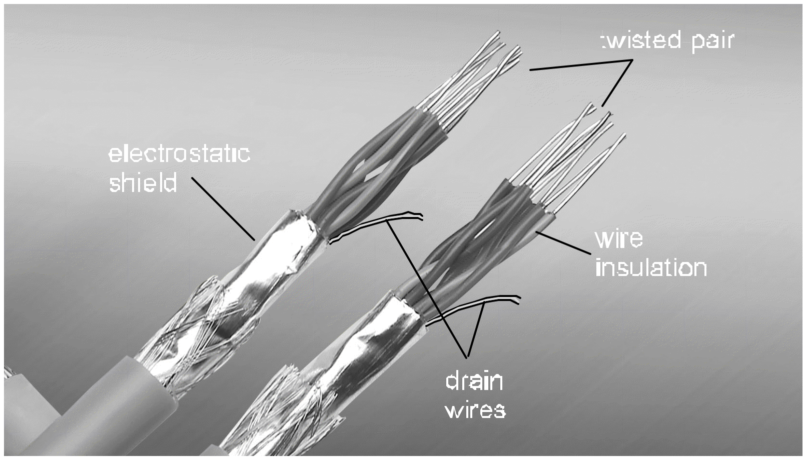


**Figure 10.8: Multipair Cables Showing Twisted Pairs (from Belden CDT)**

## 10.3 Noise and Electromagnetic Interference

In many instances, engineers other than electrical engineers are called upon to make decisions on cabling, wire routing, and enclosure design in systems which have an electrical aspect. Since these decisions can markedly affect the performance of the systems by allowing signals from one electrical system to interfere with signals in another electrical system, we have chosen to treat the discuss noise coupling mechanisms and noise mitigation at some length in this chapter and to give rather cursory treatment of the data acquisition. We apologize to those readers who would wish for a more detailed discussion of data acquisition and refer them to the many recent books on the topic.

Energy from one system can be coupled to another system and introduce unwanted signals. Energy can be transferred from one circuit (the source) into another circuit (the victim) via four mechanisms, each of which will be discussed below. The results of this energy transfer from the source circuit to the victim circuit can range from simple system malfunction to permanent damage of the victim circuit. The term electromagnetic interference (EMI) is used to refer to these phenomena.

From another viewpoint, techniques have been developed which allow the victim circuit to be made less susceptible to EMI—that is, they could be designed so that, for a given source, they would suffer fewer negative effects from interference. The general area of designing circuit so that they do not interfere with other circuits and that are not easily interfered with (designing circuits so they are less susceptible to EMI) is electromagnetic compatibility (EMC).

EMC is a field in which engineers from a variety of disciplines work together to solve system-level design problems. A convenient way to conceptualize EMC problems is to remember that three elements are required to allow energy to be transferred from one system to another—a source, a coupling path, and a receiver (the victim circuit is the receiver).

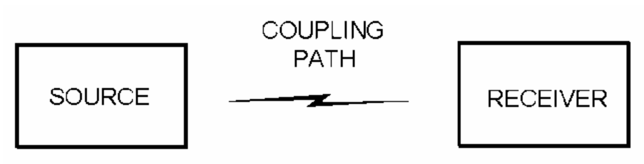


**Figure 10.9: Elements of Electromagnetic Energy**

EMI occurs is via four mechanisms: electric-field coupling, magnetic field coupling, common impedance coupling, and electromagnetic wave coupling.

### 10.3.1 *Magnetic Field Coupling*

A magnetic flux surrounds every current. The sense of the magnetic flux can be determined from the direction of current flow by the right hand rule. If the current is

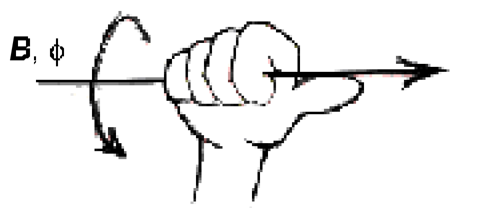


**Figure 10.10: Right-Hand Rule**

changing with time, then the magnetic flux density (***B***) and the magnetic flux (ϕ) change with time as well.

The possibility for magnetic field coupling starts with a time-varying current (in the source circuit) produces a time-varying magnetic flux. When a loop in another circuit (the victim circuit) is linked by this time-varying magnetic flux, a voltage is induced according to Faraday's law.

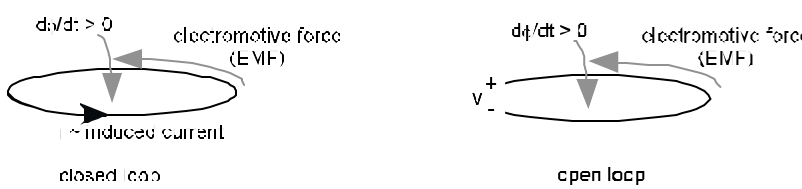


**Figure 10.11: Electromagnetic Induction**

The open loop voltage in Fig. 10.11, is determined by Faraday's law to be

$$V = -\frac{df}{dt}$$

The magnetic flux is related to the magnetic flux density via a surface integral.

$$f = \iint_{\text{loop area}} \boldsymbol{B} \bullet d\boldsymbol{s}$$

Assuming that the flux density vector, ***B***, is uniform over the entire loop area, the integral can be expressed as a product.

$$f = -B\ A \cos q$$

Where B is the magnitude of the flux density, A is the loop area and θ is determined from the directions of the flux density vector and the loop normal.

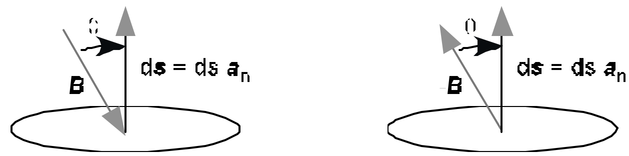


**Figure 10.12: Magnetic Flux**

Assume the current producing the magnetic flux varies sinusoidally with time (but is still uniform across the loop area).

$$B(t) = B \cos \omega t$$

In this case the magnetic flux linking the loop is

$$f = -B \cos(wt)\ A \cos q$$

Using phasor analysis, the phasor voltage induced would be

$$V = -\frac{df}{dt} \quad \rightarrow \quad \boldsymbol{V} = -jw\boldsymbol{f} = j\,wBA \cos q$$

Here, the magnitude is the quantity of interest.

$$V = w\ BA \cos q$$

This equation will prove a very convenient way of thinking about magnetic coupling. It is simple while clearly showing the parameters that determine induced voltages in a victim circuit.

For a given interfering magnetic field of frequency ω, the induced voltage into a second circuit (the victim circuit) in three ways.

1. Reduce the magnitude of B by separating the circuits.

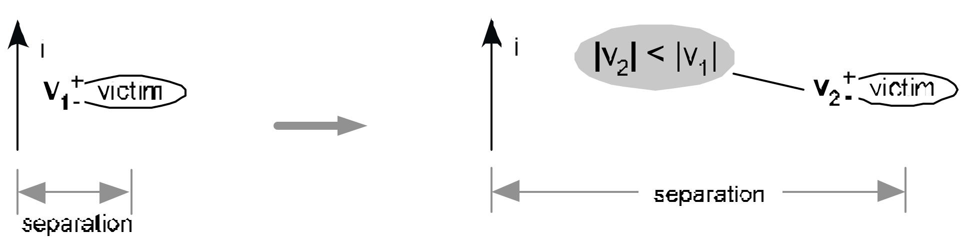

**Figure 10.13: Reduce Magnetic Coupling by Separating Source and Victim**

2. Change, θ, the orientation of the victim circuit.

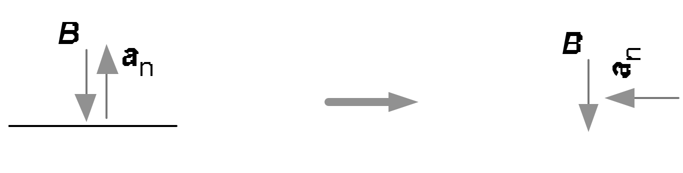


**Figure 10.14: Reduce Magnetic Coupling through Orientation**

While the simple equation above predicts that it would be possible to eliminate induced voltages entirely through orientation (after all, cos 90° = 0), most EMC engineers assume a practical limit of a factor of 100.

3. Reduce the area of the loop in the victim circuit.

The other way of controlling the voltage induced in a victim circuit is simply to reduce the area of the victim circuit.

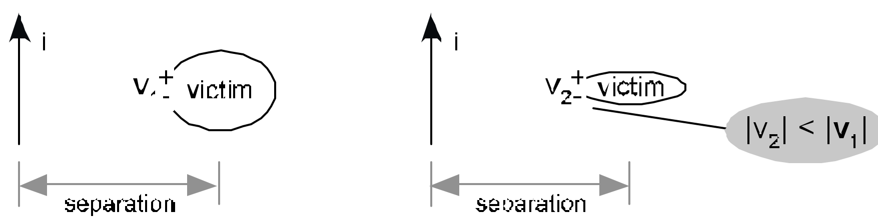


**Figure 10.15: Reduce Magnetic Coupling through Orientation**

**Example 10.1**

The use of twisted-pair wires is often used to reduce magnetic coupling. Consider the amplifier circuit shown in Fig. 10.16.

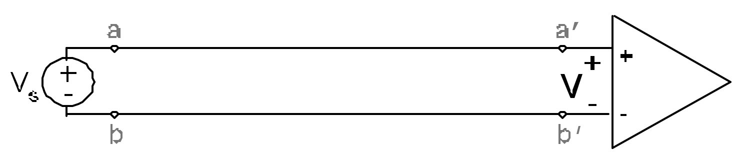


**Figure 10.16: Signal Source and Amplifier**

When no changing magnetic field is present, $V = V_S$. However, when a time-varying magnetic flux is present, the voltage induced in the loop causes the voltage at the amplifier input, V, to differ from that of the signal source, $V_S$.

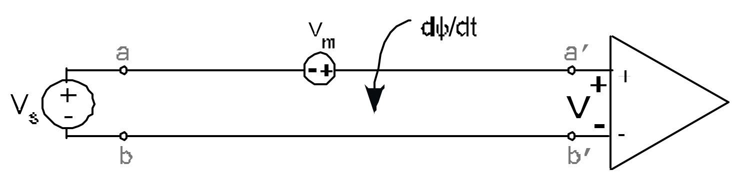

**Figure 10.17: Signal Source and Amplifier with Time-Varying Magnetic Flux**

In Fig. 10.17, $V = V_s + V_m$, where $V_m$ is the voltage induced in the loop via magnetic coupling.

How can the area linked by the flux be reduced? One way would be to simply reduce the area—reduce the length or the wide of the loop (or both). Suppose, however, that the length is fixed and that the wires are already as close together as their insulation allows. What then?

A clever and very effective way is to twist the wires. In this way, the sense of the induced voltages are opposite for neighboring loops and they partially cancel.

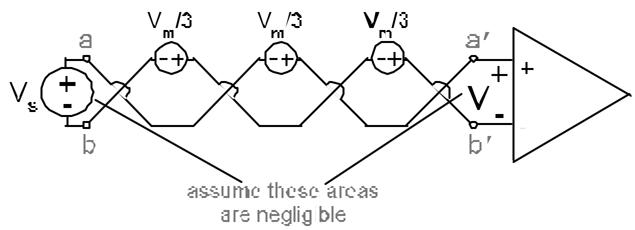


**Figure 10.18: Using Twist-Pair to Reduce Magnetic Coupling**

By KCL, $V = V_s - V_m/3 + V_m/3 + V_m/3 = V_s + V_m/3$. Suppose that there were seventy-one loops rather than three. What would the voltage at the amplifier input be? For seventy-one loops, $V = V_s + V_m/71$. The use of twisted pair wires is the most widely used method of reducing magnetic field coupling. A wide variety of twisted pair cabling is available from cable manufacturers.

What would occur if the number of twists were even? The simple model used here predicts that the induced voltage could be eliminated entirely. Such is not the case. In general, the voltage is $V = V_s + V_m/N$, where N is the number of twists.

One additional caveat should be mentioned. The formula suggests that voltage induced can be continually reduced merely by increasing N. The practical limit used by most workers in EMC is a factor of 1000. If N is greater than a thousand, it is assumed that the voltage induced via magnetic coupling is therefore reduced by the maximum amount possible through the use of twisted pair—a factor of 1000.

### 10.3.2 *Electric Field Coupling*

Electric field coupling exists anytime there is a voltage difference between conductors. This coupling is modeled by including a capacitance between these conductors. In this view, the conductors become capacitor plates with the electric field between them. Because electric field coupling is modeled using capacitance, it is often referred to as capacitive coupling.

This capacitance is not an intentional component. That is no one has placed a capacitor placed between the two circuits. Nevertheless, there is a capacitance which couples the circuits. This unintentional capacitance, which models capacitive or electric field coupling is often referred to as a parasitic capacitance.

Consider two circuits with capacitive coupling. One is the source circuit (V driving a load modeled as the resistance R). The other is the victim circuit, modeled as a non-ideal voltage source driving an RC load ($R_L$ and $C_L$ in parallel).

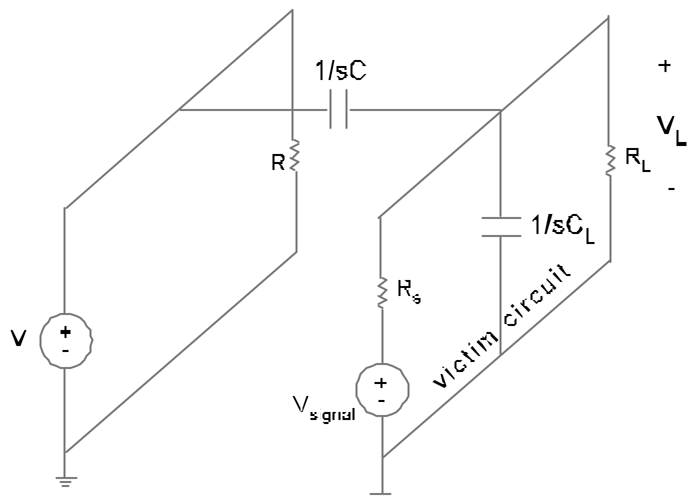


**Figure 10.19: Two Circuits with Electric Field Coupling**

Using superposition, the signal load voltage, $V_L$, has two components—the intended signal due to $V_{signal}$ and the unintended interference due to V.

$$V_L = V_L\big|_{\text{due to } V_{signal}} + V_L\big|_{\text{due to } V}$$

To find $V_L|_{\text{due to V}}$ the equivalent circuit is

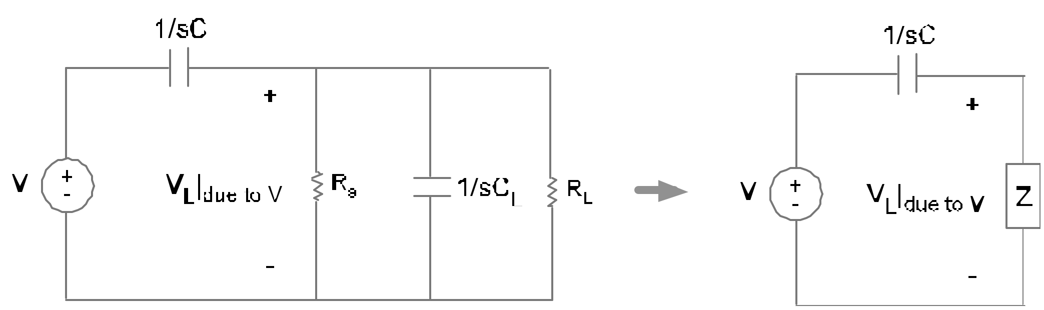


**Figure 10.20: Simplified Coupling Model**

From the simplified model, the dependencies for the coupled voltage are clear.

$$V_{L(\text{due to V})} = \frac{Z}{Z + 1/sC}V$$

The coupled voltage increases as V, Z, or C increases.

This implies, for example, that high voltage circuits can more easily interfere with other circuits than can low voltage circuits. It further means that high impedance circuits are more susceptible to electric field coupling than are low impedance circuits. It means that electric field coupling becomes more important as the coupling between them increases.

The first observation, the high voltage circuits can more readily than can low voltage circuits is seems perfectly reasonable is precisely what one would predict based upon common sense.

The second observation, the truth that high impedance circuits are more susceptible to capacitive coupling may not be as obvious. Looking at the simplified model and thinking in terms of voltage division one can readily appreciate, however, that it must hold true.

For Z to be large, the three impedances, $R_s$, $1/sC_L$, and $R_L$ must each be large. The impedance of the parallel combination is

$$Z = \left( \frac{1}{R_s} + \frac{1}{R_L} + sC_L \right)^{-1} = \frac{R_s R_L}{sC_L R_s R_L + R_s + R_L}$$

One can readily see from the expression for Z, that its magnitude will decrease as either $R_S$ or $R_L$ decreases. Increases in $C_L$ will likewise result in the magnitude of Z decreasing.

Electric field coupling can be reduced by just allowing one of these impedances to become smaller. For example, if $R_S$ grows smaller, Z also grows smaller, and the coupling becomes less efficient.

The third observation, that the coupling becomes more efficient as the coupling capacitance becomes larger clearly must be so if one considers what factors make capacitance larger. Consider the parallel plate model.

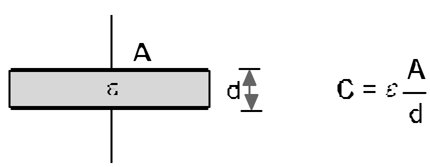


**Figure 10.21: Parallel Plate Model**

So that, if two circuits ran parallel to one another over a distance, one would expect that the two circuits would be more tightly coupled. This is exactly what is predicted from the model since, the circuits running parallel would increase their adjacent plate areas (A in the parallel plate model) which would increase C.

If the separation between circuits decreases, common sense would dictate that one should expect an increase in coupling. Again, this is exactly what the model predicts since C increase as plate separation, d, decreases.

### 10.3.3 *Common Impedance Coupling*

Common impedance coupling can results when two circuits, say circuit 1 and circuit 2, share a common impedance. The common impedance can carry currents from circuit 1, which affects the voltages in circuit 2. This is the idea of common impedance coupling.

**Example 10.2**

Consider the two-stage op-amp circuit shown in Fig. 10.22

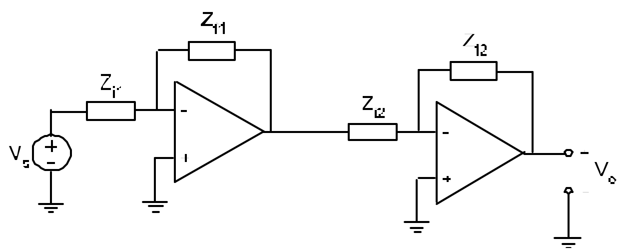


**Figure 10.22: Two-Stage Op-Amp Circuit**

Using the ideal op-amp model,

$$V_o = \frac{Z_{f1}}{Z_{i1}}\frac{Z_{f2}}{Z_{i2}}V_s$$

The positive input on both op-amps are shown to be connected to the common, but they likely are physically connected at different locations. There is no physical way that there can actually be zero impedance between these two points. They are, after all, connected using a metal which has a low but nonzero resistively. There will be an unintentional impedance between them.

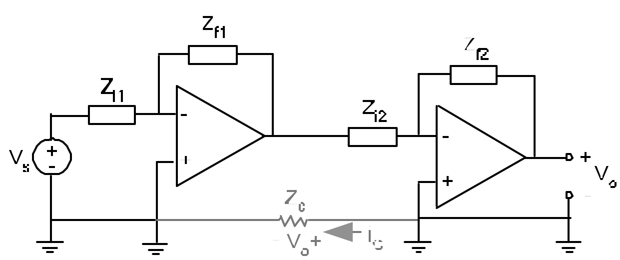


**Figure 10.23: Two-Stage Op-Amp Circuit with Nonideal Common**

A non-zero current in this unintentional impedance clearly affects the operation of the op-amp circuit. Treating $V_c$ as a source and using superposition,

$$V_o = \frac{Z_{f1}}{Z_{i1}}\frac{Z_{f2}}{Z_{i2}}V_s + \left(1 + \frac{Z_{f2}}{Z_{i2}}\right)V_c$$

The second term would represent common impedance coupling if the current $i_c$

were due to a source in another circuit.  How could this occur?  Consider the situation in Fig. 10.24.

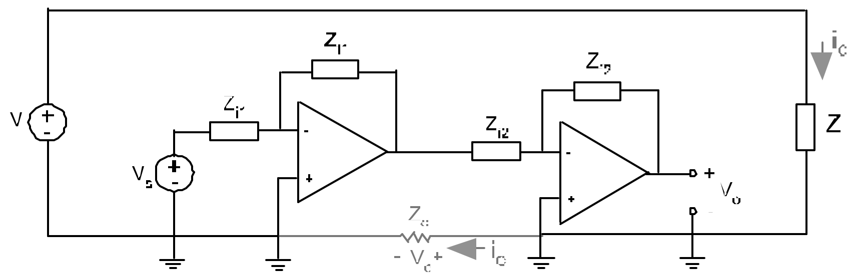


**Figure 10.24:  Common Impedance Coupling**

$$V_o = \frac{Z_{f1}}{Z_{i1}}\frac{Z_{f2}}{Z_{i2}}V_s + \left(1 + \frac{Z_{f2}}{Z_{i2}}\right)\frac{Z_c}{Z + Z_c}V$$

This example has shown common impedance coupling in the context of an op-amp circuit.  Another example would be in for a ribbon cable having several signals which share one wire in common.  Fig. 10.25 shows a ribbon cable carrying seven signals which share a common return.

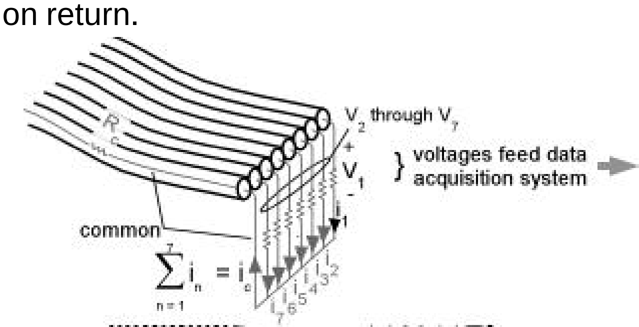


**Figure 10.25:  Common Impedance Coupling**

Since any physical return wire will have a non-zero resistance (or impedance if you prefer), a current in any one of the cables will affect the voltage across all the resistors.

### 10.3.4 *Electromagnetic Coupling and Shielding*

The electric and magnetic coupling mechanisms referred to nearly voltages and/or currents producing electric and magnetic fields which can introduce unwanted signals into a victim circuit.  Traveling electromagnetic fields can also cause unwanted signals. An overall electromagnetic shield can effective in protecting against interference by these electromagnetic fields.

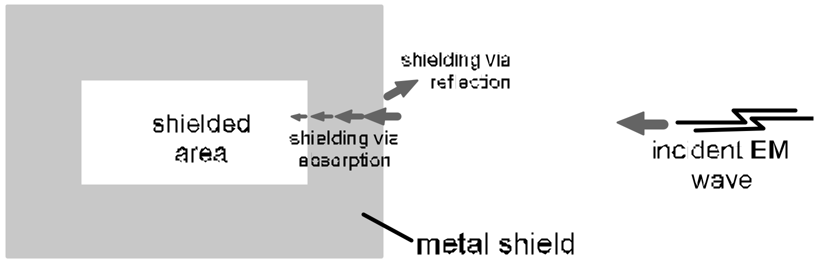


**Figure 10.26: Electromagnetic Shielding**

Electromagnetic shields are conductive materials, usually metals, which prevent electromagnetic waves from entering the shielded region. This is accomplished via reflection and absorption. Again, shields function by reflects EM energy away from the receiving circuits or by attenuating the EM wave as it travels from source to receiver.

The effectiveness of a particular shield is defined in dB as

$$S = 20 \log_{10}\left(\frac{V_{ns}}{V_{sh}}\right) = A + R$$

$V_{ns}$ ~ interfering voltage without shield
$V_{sh}$ ~ interfering voltage with shield

*Shielding effectiveness due to absorption (A)*
In a conductor, the amplitude of the electromagnetic wave decreases exponentially at a rate characterized by the attenuation constant.

$$E = E_o\, e^{-x/d}$$

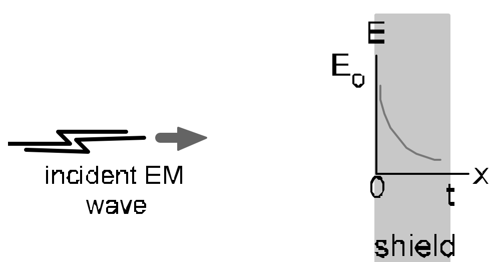


**Figure 10.27: Absorption of Traveling Electromagnetic Waves by a Conductive Shield**

The component of shielding effectiveness provided by attenuation is called the absorptive loss (A) and is measured by comparing the field with no shield to that with the shield.

$$A = 20 \log_{10}\left(\frac{V_{ns}}{V_{sh}}\right) = 20 \log_{10}\left(\frac{E_o}{E_o e^{-t/d}}\right) = 8.69\frac{t}{d}$$

δ is "skin depth." It is a function of the material properties and frequency.

$$d = \sqrt{\frac{2}{wms}}$$

where

~ ω is the angular frequency of the EM wave

~ μ is the permeability of the shield ($\mu = \mu_o$ for non magnetic shields like Cu or Al)

~ σ is the metal's conductivity

The conductivity for several metals is given in Table 10.1.

| Metal | Conductivity (S/m) |
|---|---|
| Silver (Ag) | $6.2\times10^7$ |
| Copper (Cu) | $5.8\times10^7$ |
| Aluminum (Al) | $3.7\times10^7$ |
| Brass (typ.) | $1.6\times10^7$ |

**TABLE 10.1: Conductivity of Common Metals**

Table 10.2 shows the absorptive loss for an aluminum sheet 1.5 mm thick and an aluminum coating 50 μm at several different frequencies.

| Frequency | δ | $A_{sheet}$ | $A_{coating}$ |
|---|---|---|---|
| 60 Hz | 11 mm | 1.19 dB | 0.04 dB |
| 1 kHz | 2.6 mm | 5.01 | 0.17 |
| 1 MHz | 83 μm | 157 | 5.2 |
| 100 MHz | 8.3 μm | 1570 | 52 |

**TABLE 10.2: Absorption of Aluminum Shields of Different Thicknesses**

In practice, attenuation values in excess of 100 dB are not attainable

*Shielding effectiveness due to reflections (R)*

Shielding effectiveness is not due solely to absorption—EM energy can also be reflected. The effectiveness of reflection can be calculated if the metals impedance to EM waves is known.

$$Z_m = \sqrt{\frac{wm}{s}}$$

Table 10.3 shows the impedance of aluminum at several frequencies.

| $f$ | $Z_m$ |
|---|---|
| 60 Hz | 3.58 μΩ |
| 1 KHz | 14.61 μΩ |
| 1 MHz | 461.9 μΩ |
| 100 MHz | 4.62 mΩ |

**TABLE 10.3: EM Impedance Offered by Aluminum at Various Frequencies**

The shielding effectiveness due to reflection can be calculated via the formula below.

$$R = 20\log_{10}\left(\frac{Z_w}{Z_m}\right), \quad \text{where } Z_w = \sqrt{\frac{m_o}{e_o}} = 377\ \Omega$$

The total shielding effectiveness can be found by summing the effectiveness due to absorption and reflection.

$$S = A + R$$

At low frequencies, the absorptive loss is small because the absorption increases with the number of wavelengths required to transverse the shield. Reflection peaks at low frequencies because $Z_m$ is small.

Since the attenuation shielding is small at low frequencies, just where the shielding due to reflections is large, their combination can result is an effective shield for all frequencies.

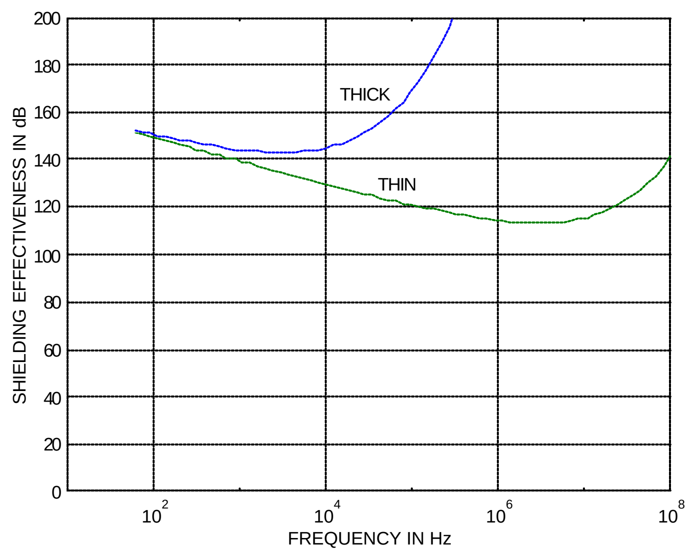

**Figure 10.28: Shielding Effectiveness Variation of Thin and Thick Shields vs. Frequency**

## Example 10.3

Consider an interfering signal at 10 GHz. Suppose 100 dB of shielding effectiveness is necessary. What thickness of copper shielding would be required?

The total shielding effectiveness is the sum of that due to reflection and that due to absorption. Since R does not depend on shield thickness, it should be found first in order to determine the required effectiveness due to absorption, A. The required shield thickness can then be determined through A.

1) Determine R for copper at 10 GHz

Aluminum is nonmagnetic so that $\mu = \mu_o$.

$\sigma_{cu} = 5.8\ (10^7)$ S/m

$$R = 20\log_{10}\left(\frac{Z_w}{Z_m}\right) = 20\log_{10}\left(\frac{\sqrt{\frac{m_o}{e_o}}}{\sqrt{\frac{wm_o}{s}}}\right)$$

$$= 20\log_{10}\sqrt{\frac{s}{we_o}} = 20\log_{10}\sqrt{\frac{5.8(10^7)\text{S/m}}{\left(2p10^{10}\text{r/s}\right)8.854(10^{-12})\text{ F/m}}}$$

$$= 80.2\text{ dB}$$

2) Determine required absorption for a total shielding effectiveness, S = R + A, of 100 dB. Since R = 80.2 dB, the shielding effectiveness due to absorption must be 19.8 dB.

$$d = \sqrt{\frac{2}{wms}} = \sqrt{\frac{2}{2p10^{10}\text{ r/s}\left(4p10^{-7}\text{ H/m}\right)5.8(10^7)\text{S/m}}}$$

$$= 0.66\ m\text{m}$$

To determine the required thickness,

$$A_{required} = 8.69\frac{t_{required}}{d} \quad \rightarrow \quad 19.8 = 8.69\frac{t_{required}}{0.66m\text{m}}$$

$$t_{required} = \frac{19.8}{8.69}0.66\ m\text{m} \cong 1.5\ m\text{m}$$

So that a very thin foil would be sufficient.

Using this shield would provide 100 dB of shielding effectiveness at 10 GHz. What does this mean practically? For example, if this traveling EM 10 GHz wave causes an unwanted 1V amplitude signal with no shield, the voltage would be reduced to 10 μV.

$$S = 20 \log_{10} \frac{V_{ns}}{V_{sh}} \quad \rightarrow \quad V_{sh} = \frac{V_{ns}}{10^{S/20}}$$

*Shield discontinuities*

The analysis developed so far has been for a continuous shield—no holes and no seams. Real shields are often not continuous--they have gaps, intentional or not.

When shields are not continuous, when holes or seams are present, they dominate the shielding effectiveness. The formulas developed above for continuous shields are of no use and must be replaced by corresponding formulas for holes.

For a given hole, a cutoff frequency can be defined.

$$f_c = \frac{15000 \text{ MHz} \cdot \text{cm}}{l}$$

where $l$ is the largest linear dimension associated with the hole (the diameter for a circular hole, the diagonal for a rectangular hole).

For frequencies below the cutoff frequency the shielding effectiveness of an infinitely thin shield (that is, no absorption) can be approximated as

$$R = 20\log_{10}\left(\frac{f_c}{f}\right)$$

Above the cutoff frequency, this formula does not hold and no shielding due to reflection is provided. For holes of non-zero thickness, there is also attenuation.

For a circular hole,

$$A = 32\frac{t}{d}$$

For a rectangular hole,

$$A = 27.3\frac{t}{l}$$

These formulas are for single holes. For multiple holes, the factor $10 \log_{10} N$ is subtracted from the single hole shielding effectiveness, S.

$$S_N = S_1 - 10 \log_{10} N$$

Often in electronic enclosures, openings must be present for cooling purposes. These opening must be designed so that the shielding integrity is not compromises. For example, a wire grid is often used over an air vent. Having many small holes is ***much*** better than one large hole.

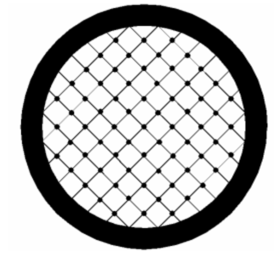

**Figure 10.29: Maintaining the Shielding Effectiveness of Large Hole Using Conductive Mesh**

Enclosures usually include seams. These seams must perform both mechanically and electrically. They must allow the current to flow freely across them. The seam can be characterized via an impedance.

To make an effective seam, surface current must not be disrupted.

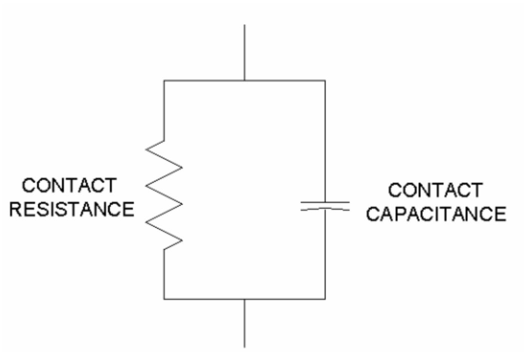


**Figure 10.30: Enclosure Seam Model**

1. The material should have a low surface resistance. Metals such as aluminum that form an oxide layer require a greater contact pressure to perform well.
2. The surface should remain free from poor conducting substances such as paint, grease, or dirt.
3. Dissimilar metals can lead to corrosive effects at their junction. Care needs to be exercised when testing each seam. Be sure to include a variety of environments.
4. Adequate contact pressure, well past the "knee" in the graph below, should be maintained to ensure free flow of surface currents.

A conductive gasket, with sufficient pliancy, can help the performance of critical seams.

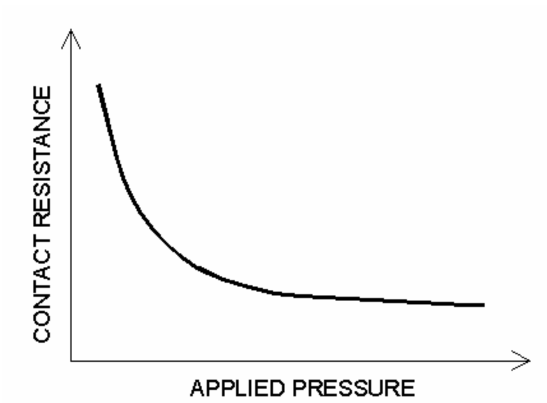


**Figure 10.31: Contact Resistance vs. Pressure for Compliant Gasket**

### Example 10.3

A transducer is attached to a machine to monitor the machine's vibration. The signals from the transducer can be as small as 100 μV. The transducer is located a distance of 20 ft away from the measuring equipment using the signal. A 60-Hz magnetic field is produced by currents associated with other machines in the factory and with the room lighting. This magnetic field has a maximum flux density of $10^{-4}$ Webers/$m^2$.

i) The accuracy of the vibration measurement can be degraded by an interfering signal as small as 1/10 of the smallest signal voltage expected from the transducer. Calculate the threshold of interference.

ii) Let the transducer be connected by two wires that are spaced 1 inch apart. Compute the amount of 60-Hz voltage induced in the circuit (assume worse case for orientation) and compare the result to the threshold of interference.

iii) Next place the wires snugly next to each other for a spacing of 0.1 inches and re-compute the induced voltage.

iv) Finally, replace the cable with a twisted pair having 8 twists/inch and compare the resulting induced voltage with the threshold on interference (assume the spacing is 0.1 inch).

*Solution*

i) $V_{threshold} = 0.1\ (100\ \mu V) = 10\ \mu V$.

ii) The formula for magnetic coupling is $V = B\omega A \cos\theta = B\omega A$ for worse case orientation ($\theta = 0°$).

$$V = 10^{-4}\ \text{Wb/m}^2\ (2p\,60\ \text{r/s})\ 20\text{ft}(12)\frac{\text{in}}{\text{ft}}\ 1\text{in}\ (0.0254\ \frac{\text{m}}{\text{in}})^2$$

$$= 5.84\ \text{mV}$$

iii) The area if reduced by a factor of 10. Therefore, V = 0.584 mV.

iv) The number of twists, $N = 20\ \text{ft}\left(12\frac{\text{in}}{\text{ft}}\right)8\ \frac{\text{twists}}{\text{in}} = 1920\ \text{twists}$.

Since N is greater than 1000, the reduction will be at the practical limit of 1000. V = 0.584 μV.

## 10.5 Data Acquisition

One frequently needs to obtain experimental data in electronic form. Once in electronic form, a variety of software tools (Matlab or Excel are two examples) can then be used for modeling, analysis, and display. What's behind this process? How is experimental data acquired by a computer system? How is the information that is collected and processed by the computer system then communicated to the user?

Experimental data is often in analog form. When using a thermocouple to measure temperature, for example, a voltage represents the temperature. The voltage is in analog form. It increases as temperature increases and decreases as the temperature decreases. For this voltage to be used by a computer, it must be converted into digital form by an analog-to-digital converter (ADC). In turn, for any information to be useful to the user, it must be converted from the binary form used by the computer into a form that can be understood by the user—typically into alphabetical characters and decimal numbers.

Below, a discussion of the binary number system (the number system used internally by computers) is followed by a discussion on the issues associated with the conversion of analog experimental quantities into binary, or digital, form.

### 10.5.1 *Binary Number System*

The value of 2 in our number system depends on where it occurs. For example, 20 refers to a different number than does 2, or 200, or 0.002. Our everyday number system of choice is the decimal system, a base-10 positional number system.

In this number system, the value of a digit depends upon its position relative to the decimal point.

$$\ldots\ \underline{10^3}\ \ \underline{10^2}\ \ \underline{10^1}\ \ \underline{10^0}\ .\ \underline{10^{-1}}\ \ \underline{10^{-2}}\ \ \underline{10^{-3}}\ \ldots$$

For example, in the decimal system 123.45 means $1(10^2) + 2(10^1) + 3(10^0) + 4(10^{-1}) + 5(10^{-2})$.

Ten digits are required in a base-10 system (0123456789). Positional number systems are powerful. They allow numbers to be manipulated quickly and easily. Find 447 + 231 for example. It is easy to bind the answer of 678.

Consider how Julius Caesar would have framed the same problem of addition. He would have posed the problem as *CDXLVII + CCXXXI.* Try performing the sum now—without using their decimal equivalents! Without converting to our base 10 system, the problem is much more difficult. Consider trying to perform multiplication or division (not to mention calculus or differential equations) with such a system.

Internally, computers use the base-2 positional number system. The base-2, or binary, system has two digits--0 and 1. The "decimal" point (in general called the radix point for systems other than base 10) gives us information on how to weight the digits based on their position.

$$\ldots\ \underline{2}^3\ \ \underline{2}^2\ \ \underline{2}^1\ \ \underline{2}^0\ .\ \underline{2}^{-1}\ \ \underline{2}^{-2}\ \ \underline{2}^{-3}\ \ldots$$

**Example 10.4**

i) Find the base-10 value of 1011.101

$$\begin{aligned} 1011.101 &= 1(2^3) + 0(2^2) + 1(2^1) + 1(2^0) + 1(2^{-1}) + 0(2^{-2}) + 1(2^{-3}) \\ &= 8 + 0 + 2 + 1 + 0.5 + 0 + 0.125 \\ &= 11.625 \end{aligned}$$

ii) Add these two base-2 numbers 1.101 + 11.11. Recall, the only digits are 0 and 1.

$$\begin{array}{r} {}^{1}1.101 \\ \underline{{}^{1}11.110} \\ 101.011 \end{array}$$

iii) Convert $13_{10}$ to binary;

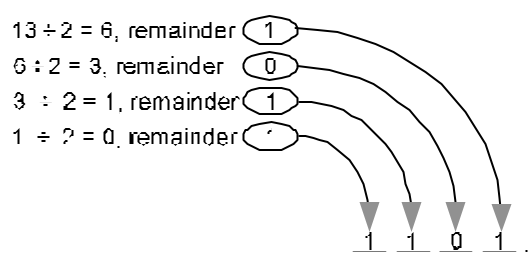


**Figure 10.32: Decimal to Binary Conversion I**

iv) Convert $13.25_{10}$ to binary.

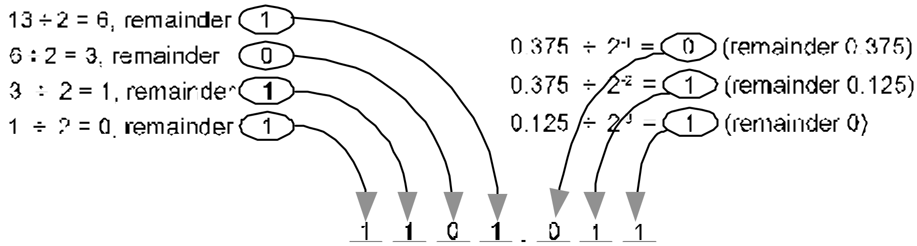


**Figure 10.33: Decimal to Binary Conversion II**

v) Convert $10011.11_2$ to decimal (base-10).

$$\begin{aligned} 10011.11_2 &= 1(2^4) + 0(2^3) + 0(2^2) + 1(2^1) + 1(2^0) + 1(2^{-1}) + 1(2^{-2}) \\ &= 16 + 0 + 0 + 2 + 1 + 0.5 + 0 \\ &= 19.5 \end{aligned}$$

The above scheme is suitable to represent positive quantities. A scheme to include negative quantities is needed. The 2's complement system can represent both negative and positive numbers.

*The development of the two's complement number system*

By definition, the sum of a number and its negative is zero. In signed binary arithmetic, the most significant digit (MSB) position is reserved for the sign digit. That is, instead of a plus or negative sign, the MSB will reserved solely to indicate the number's sign—a 0 will indicate "positive" and 1 will indicate "negative." In this scheme, the largest number that could be represented by a 4-digit binary number would be +7 (0111). Additional digits would be needed to represent larger digits.

The following procedure can be used to find any negative number. Using 7-digits (eight if the sign digit is included), find the 2's complement representation of -23.

1. The first step is to find +23 in binary. $23_{10} \rightarrow 0010111_2$.
2. Find the 1's complement by changing all zeros to ones and all ones to zeros. $0010111_2 \rightarrow 1101000_{\text{1's complement}}$
3. Note the sum of the number and its 1's complement is all ones. 0010111 + 1101000 = 1111111.
4. To obtain zero, just add 1.

$$\begin{array}{r} 1111111 \\ \underline{+\ 1} \\ 0000000 \end{array}$$

5. This implies that the negative of a binary number is formed by first finding its 1's

complement and adding 1.

6. $-23_{10} \rightarrow 1101001$. An eighth digit should be added. This will allow a 1 to be placed there to indicate the number is negative.
7. $-23_{10} \rightarrow 11101001_{2\text{'s complement}}$ (1 indicates the number is negative).

10.5.2 *Analog-to-Digital Conversion*

Analog to digital conversion occurs at the interface between the real world (perhaps an experiment or some other process) and the computer where analysis and modeling tools are readily available. When converting analog signals into their digital representations, there is a random error that results which is due to the discrete nature of the digital representation. Internally, computers use binary arithmetic. Recall binary is a positional number system. Suppose a three-digit unsigned binary number is used to represent a voltage which can vary between 0 and 4 volts. Fig. 10.34 shows this mapping. Notice that voltages anywhere between 0 and 0.5 volts will be converted to 000. If we minimize the possible error by assuming that 000 corresponds to 0.25 V, one can see that an error of ±0.25 V is possible.

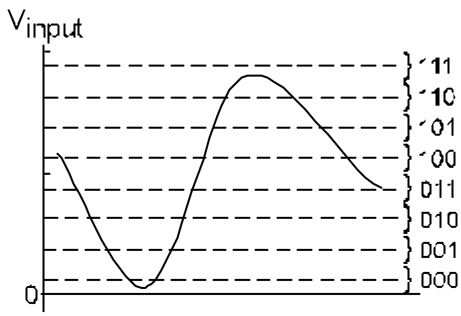


**Figure 10.34: Analog-to-Digital Conversion**

In general, the quantization error is given by

$$\text{error} = \frac{1}{2}\frac{\text{range}}{2^N} = \frac{1}{2}\frac{V_h - V_L}{2^N}$$

where N is the number of bits used. In the above example, the range would be 4 V, $V_h$ being 4 V and $V_L$ being 0. In order to obtain a digital representation with less error, additional binary digits—bits—are needed.

In using DACs, three parameters are important to a user—the number of bits, the input range, and the conversion speed. The number of bits will limit the accuracy of the measurement, the input range determine whether a given ADC can be used in a given application, and the conversion speed will limit the frequency at which conversions can be affected.

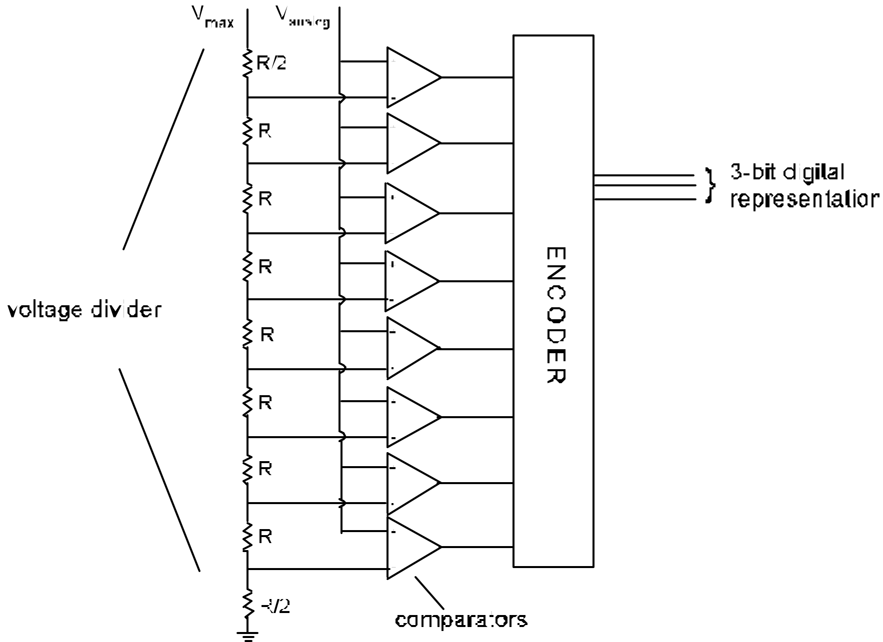


**Figure 10.35: Analog-to-Digital Conversion**

There are several types of ADCs. A parallel ADC is shown in Fig. 10.35 (a three-bit converter design is shown—practical ADCs are typically 8, 12, or 16 bit). This design permits all bits to be determined simultaneously. This strategy is good in that it is inherently fast. The cost is the additional circuitry required for the parallel implementation. Other strategies include the dual-slope integrating ADC converting and the successive approximation ADC.

### 10.5.3 *Machine-User Interface*

The character code used in Windows, DOS, and Unix is the American Code for Information Interchange (ASCII). This 7-bit code, typically stored as eight bits with the ASCII character plus a leading zero. The 128 characters in ASCII begin with 32 control characters (31 if you count the space character as a printing character). Printing characters follow these control characters.

**Control Characters** **Print Characters**

| Name | | Dec | Hex | Char | Dec | Hex | Char | Dec | Hex | Char | Dec | Hex | Char |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| null | ctrl-@ | 0 | 00 | NUL | 32 | 20 | Space | 64 | 40 | @ | 96 | 60 | ` |
| start of heading | ctrl-A | 1 | 01 | SOH | 33 | 21 | ! | 65 | 41 | A | 97 | 61 | a |
| start of text | ctrl-B | 2 | 02 | STX | 34 | 22 | " | 66 | 42 | B | 98 | 62 | b |
| end of text | ctrl-C | 3 | 03 | ETX | 35 | 23 | # | 67 | 43 | C | 99 | 63 | c |
| end of xmit | ctrl-D | 4 | 04 | EOT | 36 | 24 | $ | 68 | 44 | D | 100 | 64 | d |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| enquiry | ctrl-E | 5 | 05 | ENQ | 37 | 25 | % | 69 | 45 | E | 101 | 65 | e |
| acknowledge | ctrl-F | 6 | 06 | ACK | 38 | 26 | & | 70 | 46 | F | 102 | 66 | f |
| bell | ctrl-G | 7 | 07 | BEL | 39 | 27 | ' | 71 | 47 | G | 103 | 67 | g |
| backspace | ctrl-H | 8 | 08 | BS | 40 | 28 | ( | 72 | 48 | H | 104 | 68 | h |
| horizontal tab | ctrl-I | 9 | 09 | HT | 41 | 29 | ) | 73 | 49 | I | 105 | 69 | i |
| line feed | ctrl-J | 10 | 0A | LF | 42 | 2A | * | 74 | 4A | J | 106 | 6A | j |
| vertical tab | ctrl-K | 11 | 0B | VT | 43 | 2B | + | 75 | 4B | K | 107 | 6B | k |
| form feed | ctrl-L | 12 | 0C | FF | 44 | 2C | , | 76 | 4C | L | 108 | 6C | l |
| carriage feed | ctrl-M | 13 | 0D | CR | 45 | 2D | - | 77 | 4D | M | 109 | 6D | m |
| shift out | ctrl-N | 14 | 0E | SO | 46 | 2E | . | 78 | 4E | N | 110 | 6E | n |
| shift in | ctrl-O | 15 | 0F | SI | 47 | 2F | / | 79 | 4F | O | 111 | 6F | o |
| data line escape | ctrl-P | 16 | 10 | DLE | 48 | 30 | 0 | 80 | 50 | P | 112 | 70 | p |
| device control 1 | ctrl-Q | 17 | 11 | DC1 | 49 | 31 | 1 | 81 | 51 | Q | 113 | 71 | q |
| device control 2 | ctrl-R | 18 | 12 | DC2 | 50 | 32 | 2 | 82 | 52 | R | 114 | 72 | r |
| device control 3 | ctrl-S | 19 | 13 | DC3 | 51 | 33 | 3 | 83 | 53 | S | 115 | 73 | s |
| device control 4 | ctrl-T | 20 | 14 | DC4 | 52 | 34 | 4 | 84 | 54 | T | 116 | 74 | t |
| neg acknowledge | ctrl-U | 21 | 15 | NAK | 53 | 35 | 5 | 85 | 55 | U | 117 | 75 | u |
| synchronous idel | ctrl-V | 22 | 16 | SYN | 54 | 36 | 6 | 86 | 56 | V | 118 | 76 | v |
| end of xmit block | ctrl-W | 23 | 17 | ETB | 55 | 37 | 7 | 87 | 57 | W | 119 | 77 | w |
| cancel | ctrl-X | 24 | 18 | CAN | 56 | 38 | 8 | 88 | 58 | X | 120 | 78 | x |
| end of medium | ctrl-Y | 25 | 19 | EM | 57 | 39 | 9 | 89 | 59 | Y | 121 | 79 | y |
| substitute | ctrl-Z | 26 | 1A | SUB | 58 | 3A | : | 90 | 5A | Z | 122 | 7A | z |
| escape | ctrl-[ | 27 | 1B | ESC | 59 | 3B | ; | 91 | 5B | [ | 123 | 7B | { |
| file separator | ctrl-\ | 28 | 1C | FS | 60 | 3C | < | 92 | 5C | \ | 124 | 7C | \| |
| group separator | ctrl-] | 29 | 1D | GS | 61 | 3D | = | 93 | 5D | ] | 125 | 7D | } |
| record separator | ctrl-^ | 30 | 1E | RS | 62 | 3E | > | 94 | 5E | ^ | 126 | 7E | ~ |
| unit separator | ctrl-_ | 31 | 1F | US | 63 | 3F | ? | 95 | 5F | _ | 127 | 7F | DEL |

**TABLE 10.4: American Standard Code for Information Interchange (ASCII)**

In the 1990's, Unicode, a 16-bit code with a 32,768 characters possible, was developed. The first 128 characters of Unicode is the ASCII code with a zero first byte. The intent of Unicode is to establish a character code with sufficient characters so that more languages can be treated on an equal footing. Prior to Unicode, there were many different character codes being used, of which ASCII was one.

Apple, HP, IBM, Microsoft, Oracle, Sun, Sybase, Unisys and others, have adopted the Unicode Standard. Unicode is required in XML, Java, JavaScript, and others. It is supported by many operating systems and by all modern browsers.

## 10.6 Summary

Any engineer, faced with a measurement task, must first define the system and decide how to model their measurement task. In choosing the components to include in the measurement system being design, the engineer must consider environmental factors (temperature, pressure, vibration, humidity, corrosives, etc) in choosing and designing the sensor subsystem.

Once the preliminary design for the sensor subsystem is complete, the engineer must next consider whether signal conditioning is necessary. Signal conditioning can involve changing the form of the signals. This could, using a strain gage as an example, involve converting the change in resistance, $\Delta R$, into a change in voltage, $\Delta V$. Other possibilities would include $\Delta C \rightarrow \Delta V$ (for capacitive sensors) or $\Delta L \rightarrow \Delta V$ (for inductive sensors). Other forms of signals conditioning include overvoltage protection, buffering, amplifying, filtering, etc.

One important system-level consideration in any measurement system is noise control and mitigation. Noise and electromagnetic interference must be considered in the design stage in order to avoid the sometimes costly consequences of not doing so. Noise control and mitigation will only become more important as systems speeds increase and working voltage levels decrease.

Once the preliminary designs for the sensor and signal conditioning subsystems have been designed, and noise control been adequately addressed, the signals are often stored in electronic form using a computer. This step typically involves analog-to-digital conversion and a communication link to the computer. Data acquisition is readily accomplished via data acquisition modules with the requisite software, both of which are available from many manufactures. Many manufactures market data acquisition systems which include the necessary hardware and software to accomplish various data acquisition tasks. This area is evolving much too rapidly to include many specifics in a textbook. One recent advance is the wide availability of data acquisition modules with Universal Serial Bus (USB) interfaces. Many routine data acquisition tasks can be readily accomplished with these USB modules together with a laptop computer.

## 10.7 Computer Tools and Other Resources

MATLAB, with its graphical modeling module SIMULINK, are powerful aids in modeling many types of dynamic systems, including sensors and signal-conditioning subsystems. Techniques to model electromagnetics including finite elements, finite difference time-domain (FDTD), method-of-moments, and partial-element equivalent circuit (PEEC). One commercial provider of electromagnetic modeling packages is Ansoft.

## 10.8 Design Examples

*Magnetic Coupling Experiment*

**Objectives**

To investigate magnetic coupling and its mitigation.

**Equipment**

Function Generator
Oscilloscope

**Procedure**

1. Construct system shown below. The experimental setup shown allows the demonstration of magnetic coupling from the source circuit (driven by the function generator) to the receiving, or victim, circuit. An oscilloscope can monitor the voltage induced in the victim circuit. To observe the induced voltage, it may be necessary to use an oscilloscope with an averaging feature.

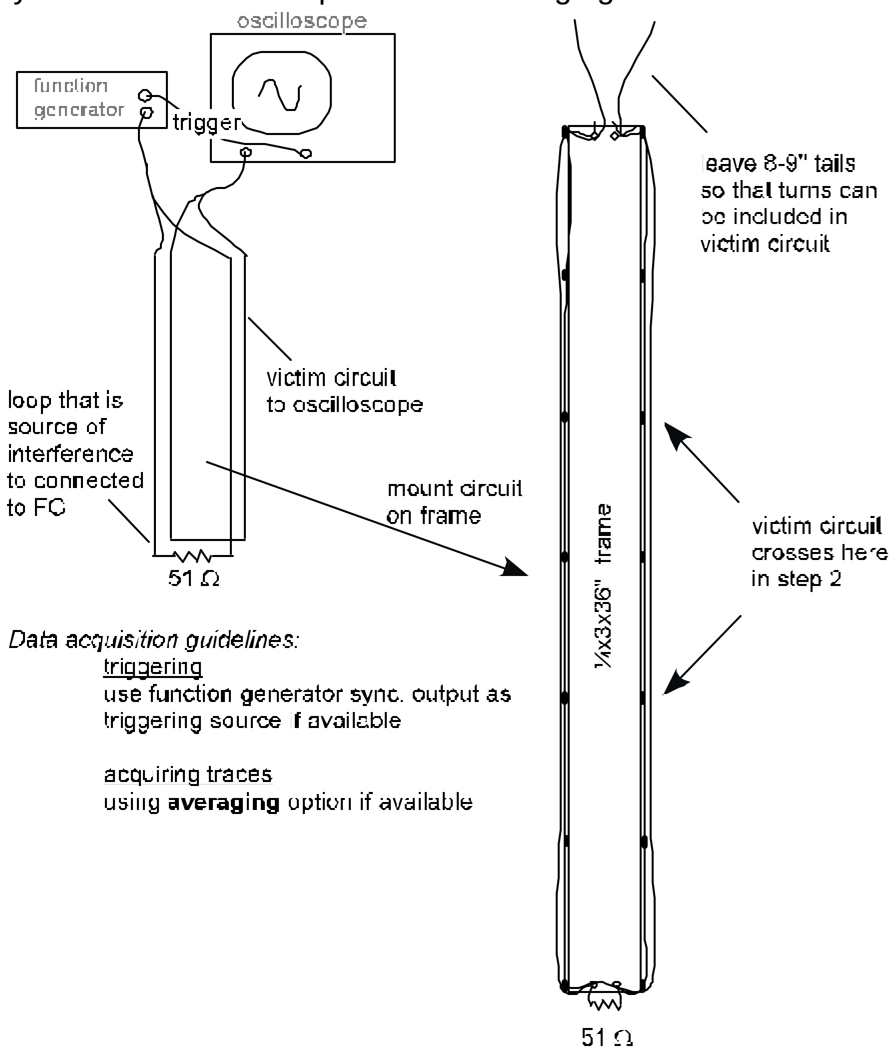


**Figure 10.36: Magnetic Coupling Experimental Setup**

| FG setting | | | observed magnetically coupled voltage ($V_{pp}$) |
|---|---|---|---|
| $V_{pp}$ (V) | f (kHz) | waveform | |
| 4 | 500 | sinusoid | |
| 4 | 5000 | sinusoid | |
| 8 | 500 | sinusoid | |
| 8 | 5000 | sinusoid | |
| 5 | 1 | square | (observe with oscilloscope adjusted to 200µs/div) |
| show trace for square wave<br><br>explain trace shape | | | |

**TABLE 10.5 Magnetic Coupling Experiment I**

2. Reconnect victim circuit for three loops. That is, cross the wires in the victim circuit so that three loops are formed.

| FG setting | | | observed magnetically coupled voltage |
|---|---|---|---|
| $V_{pp}$ (V) | f (kHz) | waveform | |
| 4 | 500 | sinusoid | |
| 4 | 5000 | sinusoid | |
| 8 | 500 | sinusoid | |
| 8 | 5000 | sinusoid | |
| 5 | 1 | square | |

**TABLE 10.6 Magnetic Coupling Experiment II**

3. From your observations with sinusoidal voltages, give correlations between source and voltage induced in victim circuit.