IEEE

EMC Experiments and Demonstrations Guide

Prepared by the
Education and Student Activities
Committee of the

IEEE EMC Society

Contents

Introduction

This document, produced by the Education and Student Activities Committee (ESAC) of the IEEE Electromagnetic Compatibility Society (EMCS) is intended to be a source of material for courses, laboratory experiments and demonstrations on the subject of Electromagnetic Compatibility. The material is organized in rough order of difficulty and audience, with the earlier experiments needing basic equipment and suitable for high school or freshman/sophomore undergraduates, and later entries requiring more specialized tools and aimed at junior/senior level engineering students.

The document is not the work of any one individual, rather a compilation of material submitted by many individuals. We thank these contributors for lending their time and expertise to this project. Comments and/or criticisms of this document, as well as any EMC demonstrations or experiments that you would like to have considered for inclusion in future editions of this booklet should be sent to the ESAC Chair.

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Electrostatic Discharge

Tony Nasuta
Westinghouse Electric Corp.

1. Objective

To demonstrate how an electrically conductive surface in physical contact with a charged dielectric can be inconspicuously charged to very high voltages. The voltages can cause damage to semiconductor electronic devices such as microprocessors, operational amplifiers, and other electronic devices if the energy stored on the conductive surface is discharged through the device.

2. Equipment

- Aluminum sheet, 1/8 inch thick, 1 to 2 square feet in area.
- Wooden handle for aluminum sheet.
- Crude spark gap consisting of two roundhead bolts 3/8 inch to 1/2 inch apart (or a neon lamp).
- Teflon sheet having approximately the same dimensions as the aluminum sheet. A thickness of 1/4 inch will give some weight to the sheet and hold it in place.
- Several feet of high voltage wire.
- Low voltage hookup wire as needed.
- Wool cloth.
- Miscellaneous flathead wood and machine screws.

3. Procedure

1. Using the materials described above, construct an aluminum plate with a sturdy wooden handle mounted on the top with countersunk flathead screws. No hardware can protrude from the bottom of the plate.
2. On a nonmetallic table construct a simple spark gap using the two bolts separated by 3/8 inch to 1/2 inch. Connect one side of the spark gap to earth ground. Using the high voltage wire, connect the other side of the gap to the top of the metal plate using a countersunk flathead screw such that no hardware protrudes through the bottom of the plate. (Or connect the neon lamp in place of the spark gap.)
3. Place the Teflon sheet on the table. Connect a low voltage wire to earth ground and place near the Teflon sheet on the table.
4. Rub the Teflon briskly with the wool cloth.
5. Place the aluminum plate on top of the Teflon sheet.
6. Momentarily ground the top of the aluminum sheet with the low voltage ground wire.
7. Quickly separate the aluminum plate from the Teflon sheet and a spark will jump the spark gap formed by the bolts (or the neon lamp will flash).

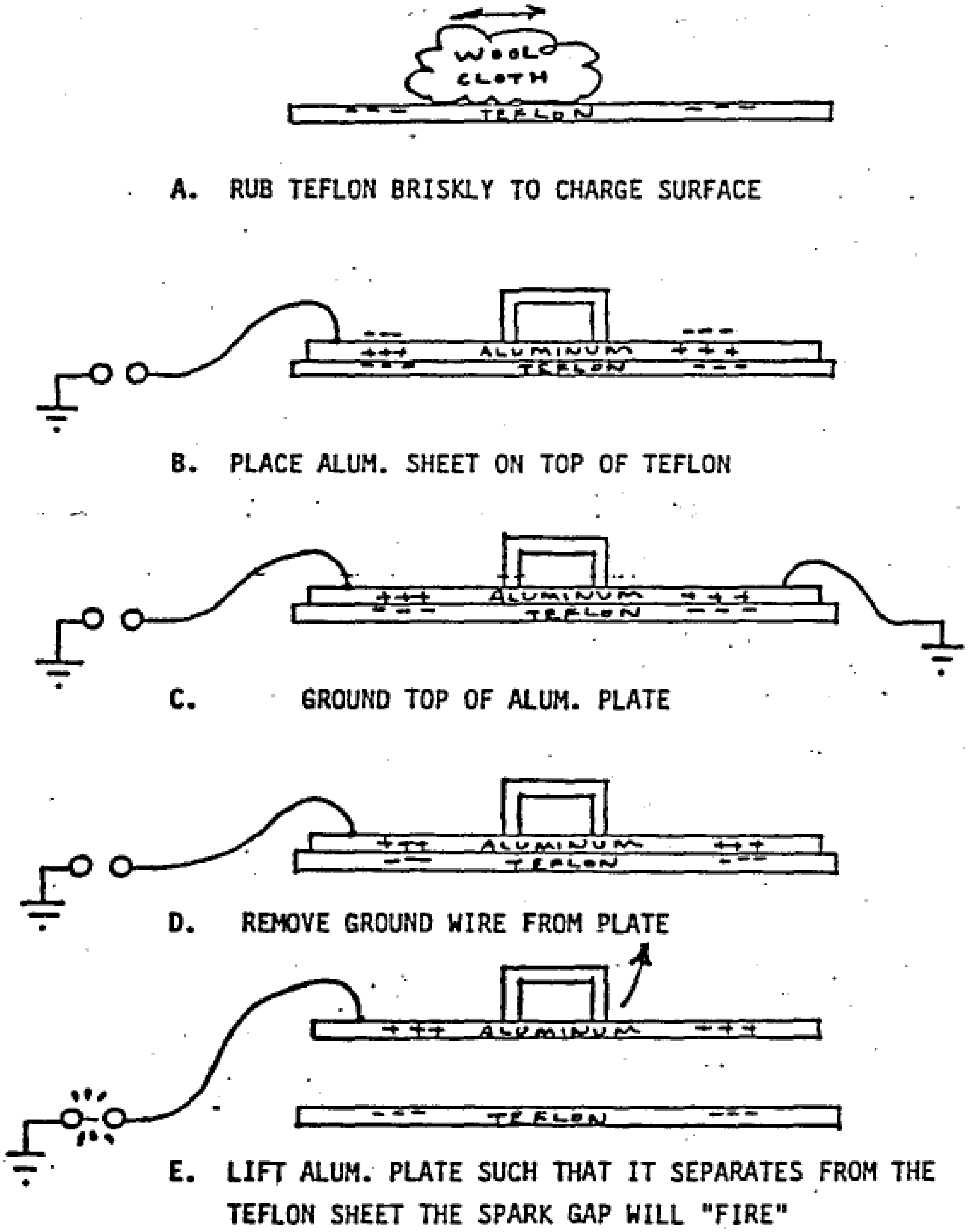

Figure 1. Electrostatic discharge experiment using Volta's electrophorous generator.

4. Theory

This experiment uses the principle of the Electrophorus Generator. Referring to Figure l(a), when the Teflon plate is rubbed with the wool, the Teflon becomes negatively charged. Placing the aluminum plate on top of the Teflon causes the neutral charge on the plate to separate, - on top, + on the bottom as shown in Figure l(b). When the plate is momentarily grounded, as in Figure 1(c), the negative charge is conducted off the plate, leaving a net positive charge on the plate, as in Figure l(d). When the plate is quickly separated from the Teflon sheet in Figure 1(e) a very high potential will develop on the plate causing the spark gap to fire. If an NRD voltmeter is available, voltages as high as 100 kV can be measured if conditions are right. Very little of the negative charge on the Teflon is removed in this process, and it may be used over and over to produce additional sparks.

Inadvertent contact of conductive surfaces with charged dielectric surfaces can induce charge and thereby impart a potential to the conductive surface. If the conducting surface were part of an electronics printed circuit board containing semiconductor devices, damage could occur in subsequent handling of the printed circuit boards. This demonstrates that care must be taken in handling and transporting such devices to prevent damage due to electrostatic discharge.

“Rusty Bolt” Demonstrator

Raymond F. Elsner
Martin Marietta Aerospace

1. Objective

To demonstrate the interference potential of random, natural nonlinear junctions between two pieces of lightly-contacting metal ("rusty bolts"). This "rusty bolt" phenomenon has generated severe interference in such diverse environments as ships [1] and large reflector antennas [2] and has been utilized in special radars [3].

2. Equipment

- Ordinary pocket AM transistor radio modified as described below.
- Two 6 inch leads with alligator clips.
- One 1000 ohm resistor.
- Rusted nut and bolt combination in which the nut can still turn on the bolt.
  - Because of the variability of actual rusted bolts it is sometimes expedient to use less-critical substitutes for demonstration purposes. Ordinary long-nose or side-cutting pliers, of the type used for electronics work, are much less critical examples. The nonlinear junction ("rusty bolt") occurs in the joint between the two pieces of hardened metal. Other useful combinations that can be used are loosely contacting metal objects such as chain links, screwdriver blades, aluminum pieces, brass hardware, etc.

3. Procedure

1. Modify the AM radio by removing the second detector semiconductor diode and solder the two 6 inch leads in its place. (Some newer radios do not have a discrete second detector diode. Rather it is contained in an integrated circuit. In this case, the experiment cannot be done with this type of radio.)
2. Connect the removed second detector diode between the alligator clips (Figure 1) and the radio plays normally. Observe polarity of the diode. Distortion will occur with improper polarization because dc bias is used on the semiconductor diode.
3. Observe that the radio will not play when the leads are open, shorted, or terminated in a resistor.

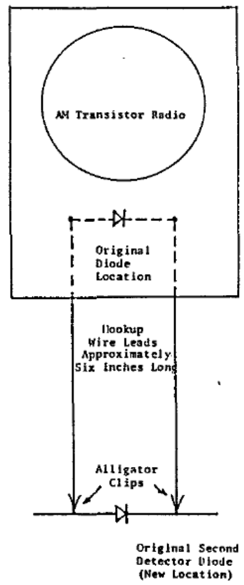

Figure 1. Transistor radio modification.

4. Connect one lead to the rusty bolt and the other to the nut. Turn the nut on the bolt until the radio plays, usually with reduced volume. Be sure that low-resistance connections are made to the bolt and nut. The alligator clips may be applied to cleaned sections of the nut and bolt or, if desired, short wires may be soldered to the nut and bolt to facilitate testing. If pliers are used in place of the "rusty bolt", connect the clips to the handles of the pliers. Open and close the pliers slowly until the radio plays.

4. THEORY

The fact that the radio plays when the "rusty bolt" is connected across the leads demonstrates the nonlinearity of the "rusty bolt". The "rusty bolt" is not a diode per se, but is a more-or-less symmetrical nonlinearity (Figure 2) having a metal-oxide-metal or metal-oxide-oxide-metal configuration.

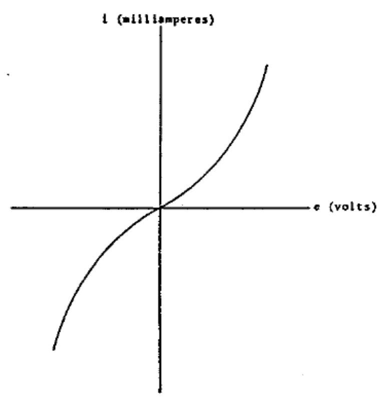

Figure 2. “Typical” nonlinear voltage-current characteristic curve.

A rusted-shut nut or bolt combination is usually either open-circuited or shorted; however, a rusty combination in which the nut can be turned can usually be adjusted to produce rectification. This adjustment is usually critical and, when operating as desired, is usually very sensitive to physical pressure. This demonstrates why "rusty bolt" generated harmonics and intermodulation products are usually extremely noisy and erratic in level.

5. References

1. Elsner, R.F. et al., "Environmental Interference Study Aboard a Naval Vessel", 1968 IEEE Electromagnetic Compatibility Symposium.

2. Higa, W.H., "Spurious Signals Generated by Electron Tunneling on Large Reflector Antennas" Proceedings IEEE, Vol. 62, No.2, Feb. 1975.

3. Optiz, C. L., "Metal-Detecting Radar Rejects Clutter Naturally", Microwaves, pp. 12-14, August 1976.

Inductance and Capacitance

Richard E. DuBroff and James L. Drewniak
University of Missouri Rolla, EMC Laboratory

1. Objective

The purpose of this experiment is to demonstrate the concepts of self and mutual inductance and capacitance. From the viewpoint of electromagnetic compatibility, capacitance and mutual inductance can provide undesired coupling paths between noise sources and susceptible victim circuits.

2. Equipment

- A set of planar inductors (see Note on Construction at the end of the section). Inductors L5 and L3 are shown in Figure 1 as examples.
- HP 4262A or HP 4263B LCR meter. The HP 4262A is shown on the left and the HP 4263B is shown on the right.
- Two standard copper pipes, each 4' long with a 1" internal diameter
- Wooden test stand to hold the pipes parallel and approximately 1 1/2" apart (center to center)
- Two 5' long RS232 cables.
- An aluminum sheet, not shown in Figure 1

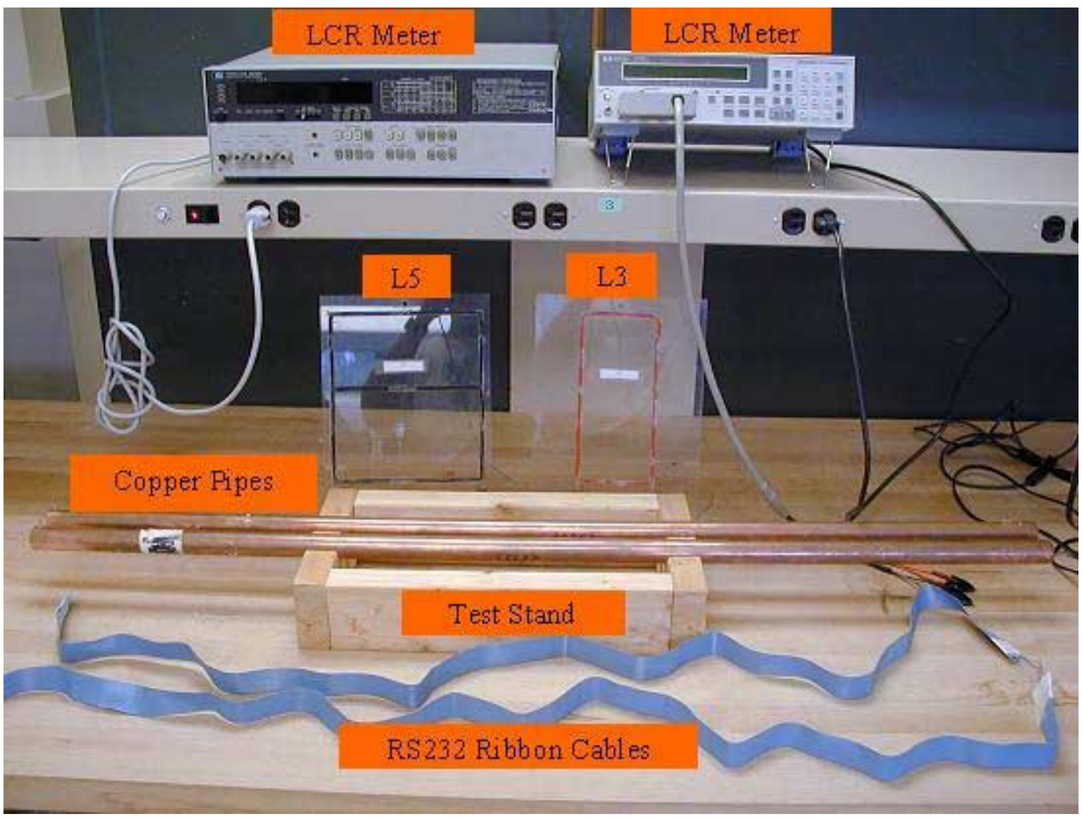

Figure 1.

3. Procedure

1. Self inductances of rectangular loops

Inductors L_1 , L_2 , and L_3 each consist of eight turns of wire wound around a rectangular loop. In each case the length of the loop is the same but the width is different. Measure the inductances (at 1 kHz) of L_1 , L_2 , and L_3 and note the trend of these values as a function of the loop width.

2. The effect of nearby metal conductors
Measure the inductance of L_3 at the lowest frequency available on the LCR meter. Then place L_3 on top of the aluminum sheet and measure the inductance again. Repeat this pair of measurements for test signals at all of the frequencies available on this LCR meter comparing the inductance with and without the aluminum sheet.

3. Mutual Inductance
Inductor L_4 is essentially identical to inductor L_1 . Fasten the back of inductor L_4 to the back of inductor L_1 by placing machine bolts through the mounting holes in the Lucite. Using the LCR bridge, measure the inductance for each of the following four configurations.

	Measurement 1	Measurement 2	Measurement 3	Measurement 4
L1 Red	To LCR “L”	NC	To LCR “L”	To LCR “L”
L1 Black	To LCR “H”	NC	To L4 Red	To L4 Black
L4 Red	NC	To LCR “L”	To L1 Black	To LCR “H”
L4 Black	NC	To LCR “H”	To LCR “H”	To L1 Black

Note that measurements 1 and 2 provide the self inductances of L1 and L4 while Measurements 3 and 4 provide the sum of L1 and L4 plus or minus twice the mutual inductance. Therefore the mutual inductance can be found from these measurements according to either:

$$M = \frac{Max\{Meas_3, Meas_4\} - (Meas_1 + Meas_2)}{2}$$

$$M = -\frac{Min\{Meas_3, Meas_4\} - (Meas_1 + Meas_2)}{2}$$

In theory the two formulas should give the same mutual inductance but errors in the measurement will generally prevent this from happening.

4. Reduced Mutual Inductance
Replace L_4 with L_5 and repeat the same set of measurements:

	Measurement 1	Measurement 2	Measurement 3	Measurement 4
L1 Red	To LCR “L”	NC	To LCR “L”	To LCR “L”
L1 Black	To LCR “H”	NC	To L5 Red	To L5 Black
L5 Red	NC	To LCR “L”	To L1 Black	To LCR “H”
L5 Black	NC	To LCR “H”	To LCR “H”	To L1 Black

The mutual inductance calculated with either of the following two equations:

$$M = \frac{Max\{Meas_3, Meas_4\} - (Meas_1 + Meas_2)}{2}$$

$$M = -\frac{Min\{Meas_3, Meas_4\} - (Meas_1 + Meas_2)}{2}$$

should now be significantly smaller. The reduction in mutual inductance can be attributed to the figure eight configuration of L_5 . The mutual flux produced by the lower and upper "halves" L_5 will link L_1 in opposite directions thereby reducing the mutual inductance between L_5 and L_1, when compared to the mutual inductance between L_4 and L_1.

5. Capacitance

Place the two metal pipes in the test stand and measure the capacitance between the two pipes using the LCR bridge. Place a few sheets of paper on top of the pipes and place the aluminum sheet on top of the paper so that it does not make direct electrical contact with either pipe. Measure the capacitance between the two pipes again. Now connect a jumper wire between the aluminum sheet and the guard terminal of the LCR meter. Note the new value of capacitance.

6. Systems of Capacitance

Figure 2 shows a cross sectional view through the two metal pipes and the aluminum sheet.

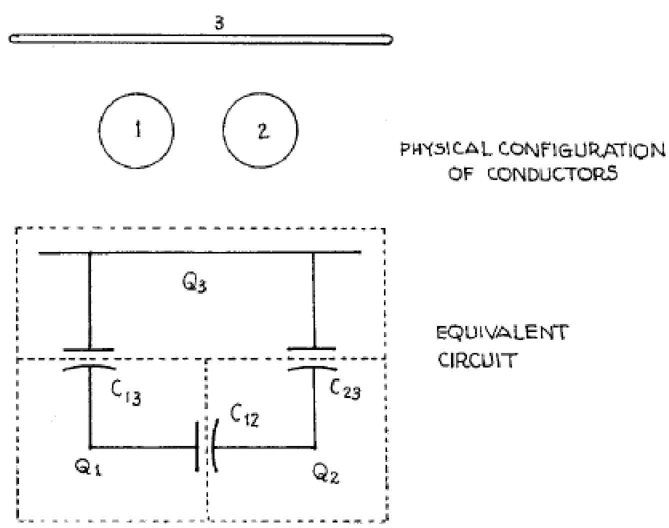

Figure 2

Considering the equivalent circuit in the lower part of this figure, the following set of measurements can be performed to determine the values of C_{12} , C_{13} , and C_{23}.

	Measurement 1	Measurement 2	Measurement 3
Conductor 1	To LCR "H"	To Conductor 3	To Conductor 2
Conductor 2	To Conductor 3	To LCR "H"	To LCR "L"
Conductor 3	To LCR "L"	To LCR "L"	To LCR "H"

Letting C_n denote the capacitance indicated in measurement n the two-terminal capacitances in the equivalent circuit model can be found from:

$$C_{12} = \frac{C_1 + C_2 - C_3}{2}$$

$$C_{23} = \frac{C_2 + C_3 - C_1}{2}$$

$$C_{13} = \frac{C_1 + C_3 - C_2}{2}$$

7. Inductance measurements of ribbon cables

There are two RS232 twenty-five conductor ribbon cables and each cable is approximately 32 mm wide. The center-to-center spacing between adjacent conductors is denoted as d_0 and is given approximately as:

$$d_0 \cong \frac{32\,mm}{25} = 1.28\,mm$$

Denoting the conductor with the red stripe as conductor 1, the shorted cable has connections between conductors 1 and 25 (Spacing = $24d_0$); conductors 3 and 23 (Spacing = $20d_0$); and conductors 10 and 16 (Spacing = $6d_0$). Connecting the LCR bridge between conductors 1 and 25, set the frequency of the bridge to 100 kHz, the voltage level to 1000 mV, and the measurement parameter to series inductance (L_s). Use the approximate formula for the inductance per unit length between a pair of parallel circular conductors:

$$L = \frac{\mu_0}{\pi} cosh^{-1}\left(\frac{d}{2b}\right)$$

where d = center-to-center spacing and b = conductor radius. A measurement of the inductance between conductors 1 and 25 can be used to find a value for b from:

$$b = \frac{d}{2cosh\left(\frac{\pi L}{\mu_0 l}\right)}$$

where L is the inductance measured between conductors 1 and 25, l is the length of the ribbon cable, and d is the center-to-center spacing between the conductors which is $24d_0$ in this case. Using this value of b, the inductance for the two other conductor pairs (3 and 23; 10 and 16) can be calculated from:

$$L = \frac{\mu_0}{\pi} cosh^{-1}\left(\frac{d}{2b}\right)$$

Where d = center-to-center spacing and b = conductor radius, and compared with the measured inductances obtained from the LCR bridge.

8. Capacitance measurements of ribbon cables

The remaining RS232 cable is open-circuited at each end and has 5 exposed conductors. By selecting various combinations, it is possible to have conductor pairs separated by spacings of $d = d_0$, $2d_0$, $3d_0$, and $4d_0$. Change the measurement parameter on the LCR bridge to yield parallel capacitance and measure the capacitance for each of the four possible spacing values. For parallel circular conductors of length l, with a center-to-center spacing of d, and a radius of b, the following approximate formula:

$$C = \frac{\pi \varepsilon l}{cosh\left(\frac{d}{2b}\right)}$$

applies if the conductors are surrounded by a dielectric with a uniform permittivity of ε. This is not the case for the ribbon cables. For small values of spacing the value of ε that makes the measured and calculated values of capacitance agree will reflect the properties of the insulating material in the ribbon cable, since the electric flux lines between closely spaced conductors will tend to be concentrated in the insulating material. With wide conductor spacings, the electric flux lines will also pass through the air surrounding the cable and so the value of ε that makes the measured and calculated values of capacitance agree will be closer to ε_0.

4. Theory and Discussion

The effect of nearby metal conductors

Eddy currents induced in the aluminum sheet tend to oppose any changes in the applied magnetic field. Since the total magnetic field passing through the wire loop is the sum of the magnetic fields produced by the applied current and the induced eddy current; the net magnetic field and hence the measured inductance should be lowered by the presence of the aluminum sheet. To explain the frequency dependence of this effect, consider an equivalent circuit for the eddy current:

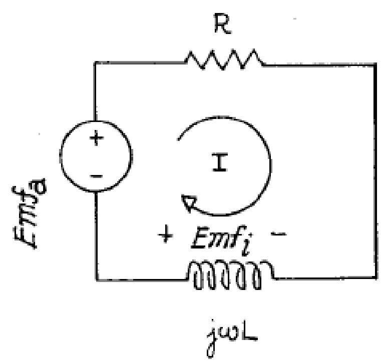

Figure 3

In this circuit, the applied magnetic field produces an applied emf (Emf_a) and the applied emf, in turn, drives the eddy current, I. The eddy current encounters a resistance (R) due to the finite conductivity of the aluminum and also a loop self inductance (L). The applied emf equals the sum of the voltage drops across the resistance and inductance in the equivalent circuit. Note that the induced emf (Emf_i) is defined to have the same polarity as the applied emf so that the net emf can be written as the algebraic sum of the applied and induced emfs. Using the standard passive sign convention this means that Emf_i as defined in the figure above is the negative of the conventional voltage drop across the loop self inductance (L).

A phasor diagram of this circuit can be constructed as shown in Figure 4.

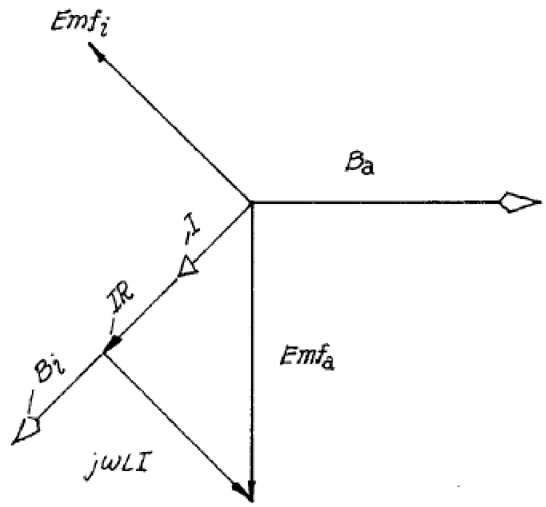

Figure 4

The applied magnetic field phasor B_a is chosen as the reference phasor. The applied emf phasor (Emf_a) is proportional to $-j\omega$ times the applied magnetic field phasor and thus is ninety degrees behind it. The applied emf, in turn, is equal to the sum of the voltage drops across the resistance and the loop self inductance. These two voltage drops must be ninety degrees out of phase, so the applied emf phasor can be regarded as the hypotenuse of a right triangle having sides defined by the resistive and inductive voltage drops. Multiplying the inductive voltage drop ($j\omega LI$) by -1 yields the induced emf (Emf_i) phasor. The induced emf phasor, in turn, is proportional to $-j\omega$ times the induced magnetic field phasor. Thus, the induced magnetic field phasor B_i is ninety degrees ahead of the induced emf, which puts the induced magnetic field phasor in phase with the induced current I.

As the frequency increases the voltage drop across the loop self inductance becomes significantly larger than the voltage drop across the resistance (assuming the resistance and inductance do not vary quickly with frequency). The result is a phasor diagram approaching that in Figure 5.

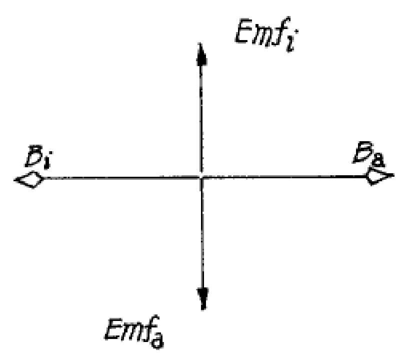

Figure 5

It can be seen that the applied and induced magnetic fields are more nearly equal and opposite resulting in a lower net magnetic field and thus a lower inductance. However the cancellation will be incomplete unless all of the applied magnetic flux enters the aluminum sheet at normal incidence.

Systems of capacitance

The equations for finding the individual two terminal capacitances came from considering the circuit shown in Figure 6 (in the case of measurement 1).

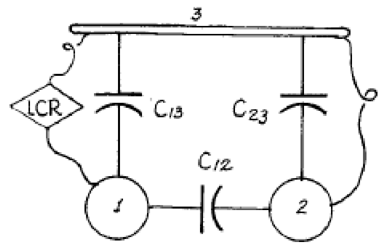

Figure 6

In this case, capacitance C_{23} has been shorted out leaving capacitances C_{13} and C_{12} connected in parallel. Thus measurement 1 should yield a capacitance equal to the sum of C_{13} and C_{12} . Similarly measurement 2 should yield a capacitance equal to the sum of C_{12} and C_{23} while measurement 3 should yield a capacitance equal to the sum of C_{13} and C_{23} . Thus to find C_{12}, for example, measurements 1 and 2 can be added together, measurement 3 can be subtracted, and the result can be divided by 2 to yield C_{12}.

The model provided by a system of capacitance can be used to look at the effect of a floating metal conductor versus a grounded metal conductor. In the Figure 7 the applied voltage at node 1 is parasitically coupled to node 2 through a system of capacitances including the capacitances associated with a floating conductor (node 3).

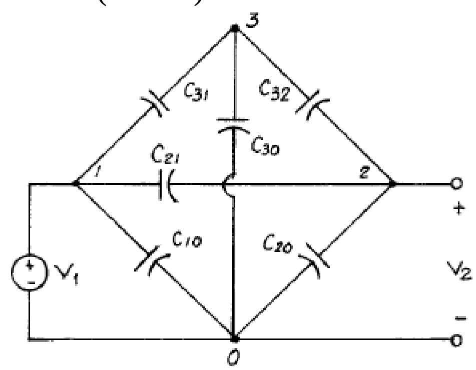

Figure 7

Note that voltages at all nodes are referenced in common to node 0. The voltage transfer function in this case can be shown to be:

$$\frac{V_2}{V_1} = \frac{C_{21} + \dfrac{C_{31}C_{32}}{C_{30} + C_{31} + C_{32}}}{C_{32} + C_{20} - \dfrac{C_{23}}{C_{30} + C_{31} + C_{32}}}$$

However, if node 3 is directly connected to the reference node, the circuit diagram is simplified considerably to that of Figure 8.

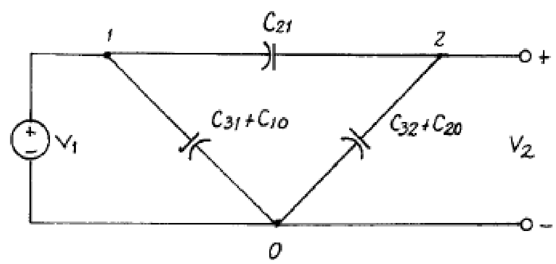

Figure 8

The voltage transfer function in this case is:

$$\frac{V_2}{V_1} = \frac{C_{21}}{C_{21} + C_{20} + C_{32}}$$

Comparing this expression with the previous voltage transfer function, the numerator in the present expression is smaller while the denominator is larger. Therefore the voltage transfer ratio should be smaller corresponding to less capacitive coupling from node 1 to node 2.

Summary and conclusions

The measurement of self and mutual inductance and capacitance at low frequencies has been demonstrated. The experiment has shown that a "twisted" conductor in a susceptible circuit can sometimes significantly reduce mutual inductive coupling. The effect of both floating and grounded metal conductors for capacitive coupling has also been demonstrated.

5. References

[1] Clayton Paul, *Introduction to Electromagnetic Compatibility*, John Wiley & Sons, Inc., New York, 1992.

[2] S. V. Marshall, R. E. DuBroff, G. G. Skitek, *Electromagnetic Concepts and Applications, 4th ed.,* Prentice Hall, Upper Saddle River, NJ, 1996.

6. Notes on Construction

Each inductor is made by placing approximately eight turns of 24 AWG plastic insulated wire into a slot on a 5/8" thick Lucite sheet. The ends of the inductors are connected to a pair of terminal posts. Refer to Figure 9.

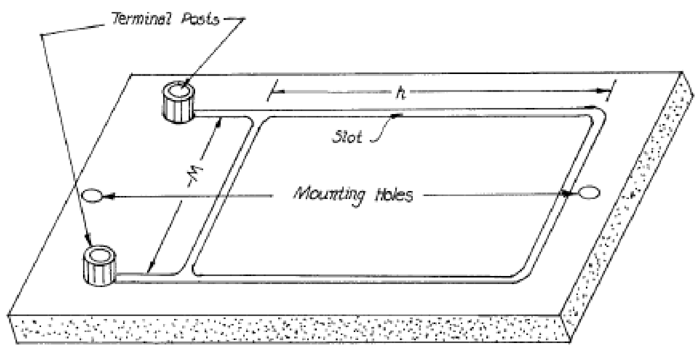

Figure 9

The dimensions for the various inductors are as follows:

Inductor	W	H
L1	8 in	9 in
L2	6 in	9 in
L3	4 in	9 in
L4	8 in	9 in
L5*	8 in	9 in

* Inductor L5 has an additional horizontal slot of length w. This slot allows the wire for L5 to be wound in a figure eight pattern so that the wire passes 16 times through the additional slot. In effect inductor L5 could be regarded as a multi-turn rectangular loop of flexible wire with the top end of the loop being twisted 180 degrees with respect to the bottom end.

For convenience, one of the terminal posts will be referred to as red and the other one will be referred to as black.

The test stand, in this case, was simply a wooden framework constructed from two by fours. A pair of notches was cut into the right and left ends of the stand (see Figure 1) to hold the copper pipes parallel to each other and approximately one and one-half inches apart (center-to-center).

The RS232 cable used for inductive measurements had one short piece of insulated wire soldered between connectors 1 and 25; another short piece of insulated wire soldered between conductors 3 and 23; and another short insulated jumper soldered between conductors 10 and 16. These jumper connections were all located at the same end of the ribbon cable. At the opposite end of the ribbon cable, conductors 1, 3, 10, 16, 23, and 25 were split off from the ribbon cable for a distance of about 1 inch and insulation was removed from each of the conductors to allow a connection to the LCR bridge test leads.

The RS232 cable used for capacitive measurements was left open circuited at both ends. However, the five center conductors (conductors 11, 12, 13, 14, and 15) were split off from the ribbon cable for a distance of about 1 inch and insulation was removed from each of these conductors to allow a connection to the LCR bridge test leads.

The Thinking Engineer's Voltage Measurement

Andy Marvin
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1. Objective

This experiment demonstrates that the measurement of a time-varying voltage requires some thought and understanding. It shows some of the pitfalls that the unwary engineer (EMC or otherwise) can fall into.

On the dual trace oscilloscope, two different voltage traces appear from two identical probes connected to the same pair of terminals. The relative amplitude of these voltage traces can be adjusted without altering the oscilloscope settings.

The experiment is an illustration of the standard Maxwell equation embodying Faraday's Law of induction (curl E = $-\partial B/dt$) and Kirchhoff's voltage law. A simple circuit is required which must be enclosed in a plastic box.

The experiment is more effective if the student has to deduce how it works rather than it being immediately apparent. The student needs to understand and apply fundamental electromagnetics in order to solve the problem.

2. Equipment

- Sinusoidal oscillator (up to 100 kHz) with preferably at least 20V p-p open-circuit voltage.
- Dual trace oscilloscope with external trigger facility operating up to 100 kHz.
- Two *identical* oscilloscope probes.
- "Curly Box" (meaning curlE box) as described below.
- Coaxial connecting cables.

Curly Box Construction

The following components are required. None are critical.

- Plastic circuit box, approximate dimensions 3"(7.6cm) x 6"(15.2cm) x 4"(10.2cm),
- AM radio ferrite antenna (rod with coil),
- Panel mounting coax socket-type, impedance, etc. not critical at these frequencies, but this works best when circuit connections are shielded,
- l kΩ resistor, carbon or film, 1/8 Watt is adequate,
- 5 kΩ linear or log single turn carbon or film potentiometer with knob
- Two through panel terminals.

The construction of the "curly box" is illustrated by the circuit and layout diagrams shown in Figures 1, 2 & 3.

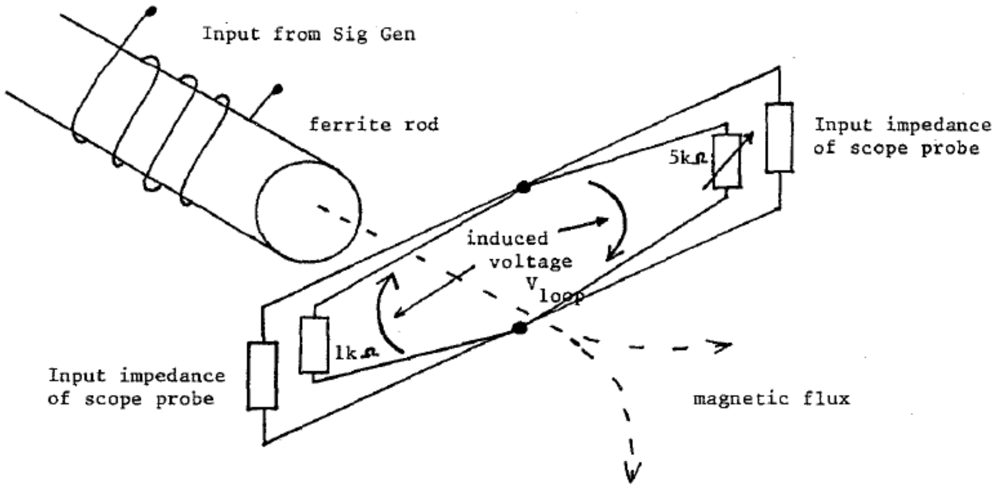

Figure 1. Circuit Diagram

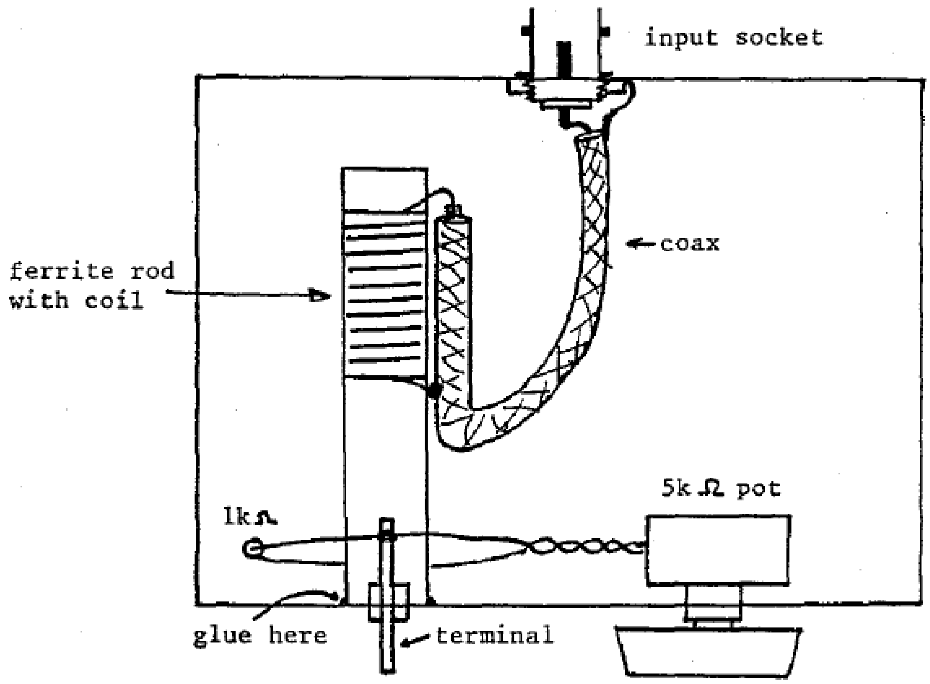

Figure 2. Component layout top view

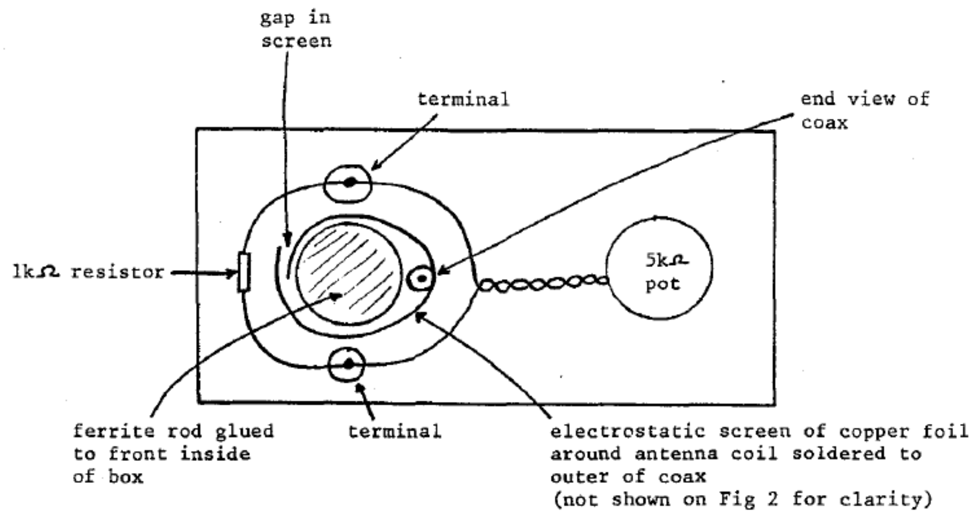

Figure 3. View of component arrangement through the front face of the box.

3. Procedure

1. Connect the apparatus as indicated in Figure 4 with the potentiometer set to around 1kΩ. A frequency of 20 kHz gives suitable results and cannot easily be heard if any magneto-strictive effects are present to cause acoustic noise. As the device operates as a step-down transformer, an input of several volts to the curly box is required to give tens of millivolts at the oscilloscope inputs. The traces on the oscilloscope should be of equal amplitude but in antiphase.
2. Turn the knob and observe the amplitudes and relative phase of the traces.
3. Explain the observations!

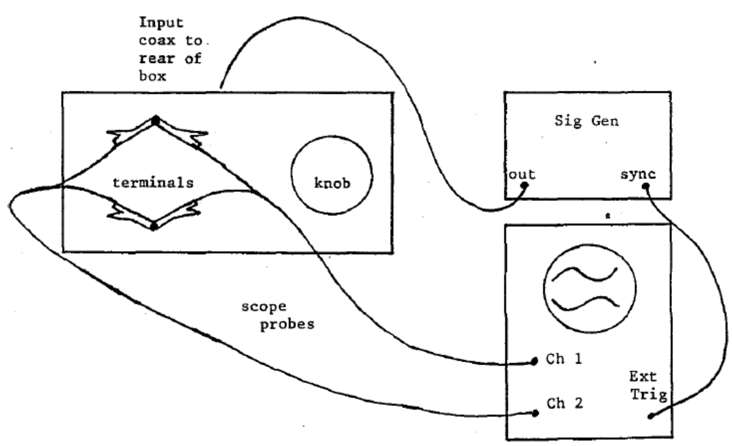

Figure 4. Experiment layout

4. Theory

Consider the loop formed by the 1 kΩ resistor and 5 kΩ pot shown in Figure 5(a). Some of the magnetic flux passes through the loop. This induces an electromotive force or emf in that loop according to Faraday's Law [1]:

$$\text{emf} = -d\phi/dt \qquad (1)$$

where ϕ is the total flux penetrating the loop. If we assume that the terminals, T1 and T2, for attachment of the oscilloscope probes are at the center of the loop, the induced emf can be divided into two equal voltage sources as shown in Figure 5(a). The voltage between the two oscilloscope probe attachment points is denoted as V_t. Using voltage division, the voltage developed between these terminal points is

$$\begin{aligned} V_t &= \frac{1}{2}emf + \left[-\frac{R1}{R1+R2}\right]emf = \frac{1}{2}emf + V1 \\ V_t &= -\frac{1}{2}emf + \left[\frac{R2}{R1+R2}\right]emf = \frac{1}{2}emf + V2 \\ V_t &= \left[\frac{R2-R1}{R1+R2}\right]\frac{emf}{2} \end{aligned} \tag{2}$$

where R1 = l kΩ and R2 = 5 kΩ (variable). Observe that if Rl = R2, then the voltage between the probe attachment points, V_t, is zero. If R2 is varied between 0 Ω and ∞ kΩ, V_t can be made to change phase 180° while the magnitude of V_t is emf/2 at these extremes. This observation is evident directly from the circuit in Figure 5(a).

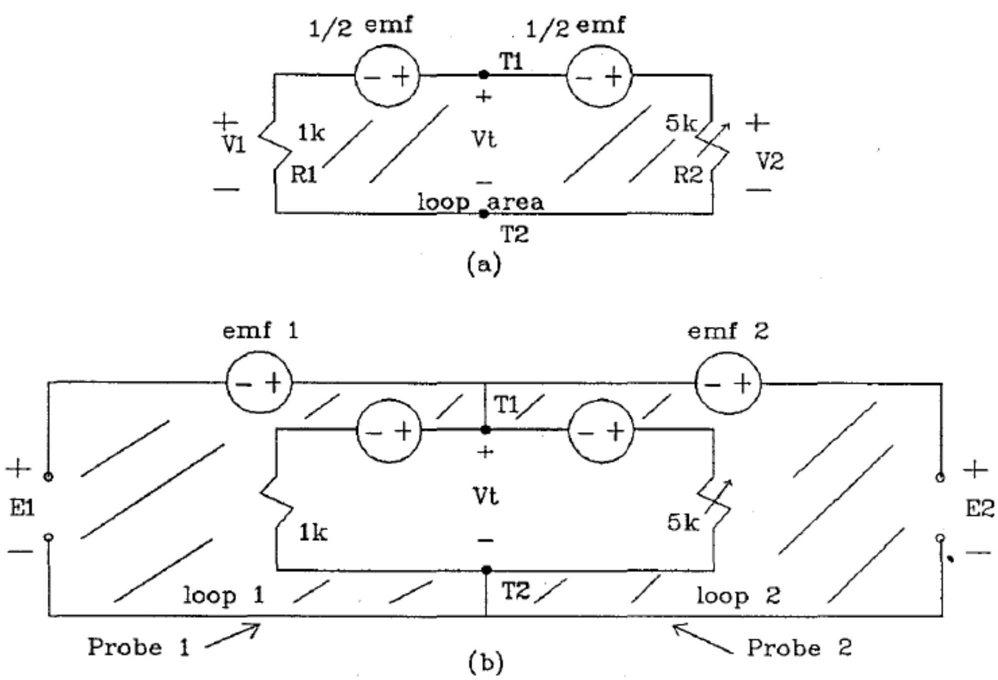

Figure 5. Illustration of the effect of induced emf's

Now consider attaching the two oscilloscope probes as shown in Figure 5(b). Let us assume that the input impedance to the two scope probes is infinite. Magnetic flux penetrates the loops formed by the scope probes, loop 1 and loop 2, inducing emf's, emf1 and emf2, in the loops. The measured oscilloscope voltages, EI and E2, then become

$$E1 = V_t - emf1 \tag{3a}$$

$$E2 = V_t + emf2 \tag{3b}$$

The positions of the scope probes and associated loop areas affect the emf's, emf1 and emf2, and hence the voltage read by the scope inputs, E1 and E2. If we assume that the two probe loop areas are equal, emf1 = emf2 = emfprobe and (3) becomes

$$El = V_t - \text{emfprobe} \tag{4a}$$
$$E2 = V_t + \text{emfprobe} \tag{4b}$$

If the 5 kΩ pot is set to l kΩ, (2) shows that $V_t = 0$ so

$$El = -\text{emf probe} \tag{5}$$
$$= -E2 \qquad Rl = R2 = l\ k\Omega$$

and the oscilloscope voltages will be antiphase.

Now suppose that R2 is set to any value other than l kΩ. Equation (4) shows that the oscilloscope voltages will not be equal with the difference depending on the relative magnitudes of V_t and emfprobe.

The engineering student is usually puzzled by two different, i.e. antiphase, voltages measured by two identical probes connected to the same terminals. At this stage the average engineering student will examine the oscilloscope settings, probe calibration, etc. and declare the oscilloscope unserviceable *(engineers think volts have to come out of terminals).* The good engineering student will do the examination of the oscilloscope, etc. and then start to think. A physics student will go straight to this stage *(physics students can't use oscilloscopes)!*

The operation of the circuit is dependent on the layout of the oscilloscope probes. The experiment is best setup before the student sees it. You can decide how much the student is allowed to move or touch the experiment in the course of her observations. For example, placing both of the oscilloscope probes on the same side of the terminals results in identical readings on both traces. Some find this a valuable clue!

5. References

1. J.D. Kraus, Electromagnetics, third edition, McGraw-Hill, NY, 1984.

Noise Measurement by Induction

Douglas C. Smith
AT&T Information System Laboratories

1. Objective

To demonstrate how to trace noise voltages and currents in circuits without direct connection to the circuit.

2. Equipment

- Pulse or function generator capable of driving at least 10 mA peak into a 50 ohm load with rise times on the order of tens of microseconds. Faster rise/fall times give better results.
- Dual trace oscilloscope with at least 50 MHz bandwidth.
- One length of 50 ohm coax: cable with a BNC connector on one end.
- Two 50 ohm terminations such as Tektronix part #011-0049-01.
- Seven feet of insulated solid copper hookup wire (18 to 22 gauge).
- A 50 ohm 1 watt carbon or metal film resistor (47 to 53 ohms acceptable).

3. Procedure

3.1 Measurement of Noise Signal

1. Form a length of the wire into a square loop one inch on a side having two turns. This loop will be used to pick up or measure the magnetic field produced by the wire currents. Connect the leads of this square loop to the free end of one coax: cable and the other end to the input of an oscilloscope through the 50 ohm termination.
2. Use about two feet of the hookup wire and a 50 ohm resistor to form a circuit as shown in Figure 1. The dimensions are not critical. Connect this circuit to the second coax: cable. Connect the other end of this coax: to the pulse generator. Connect the second scope input to the output of the pulse generator and set the scope to trigger on this waveform.
3. Set the function generator to produce repetitive 50% duty cycle pulses with a repetition frequency between 100 kHz and 1 MHz (10 ns to 50 ns rise/fall times). Set the generator for an amplitude of 5 V p-p on the oscilloscope.
4. Place one side of the square measurement loop next to and parallel to the wire carrying the function generator current. The scope trace should look like Figure 2. Adjust the oscilloscope sensitivity to give a reasonable picture of the voltage of the pickup loop. Note the shape of the trace. Slowly rotate the loop 180 degrees while holding it against the signal wire. Note how the trace goes to zero at 90 degrees and reverses phase as the loop passes 90 degrees.

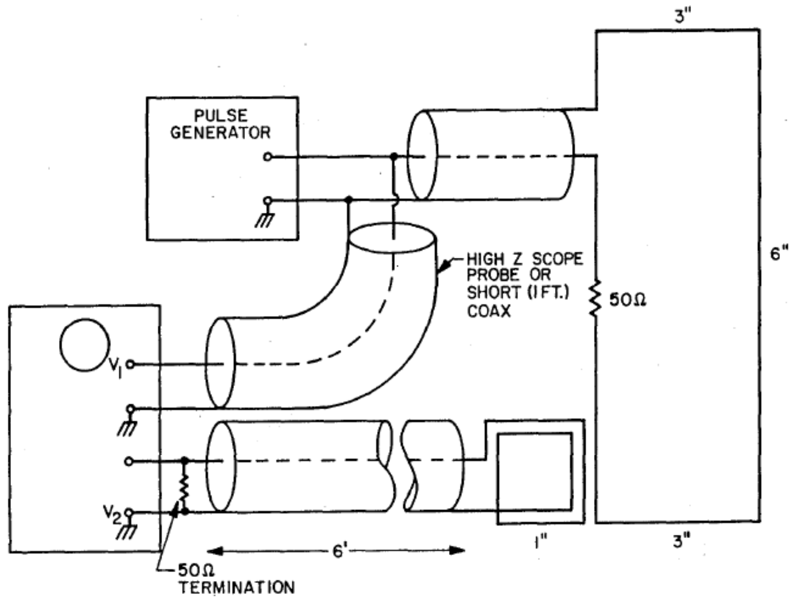

Figure 1.

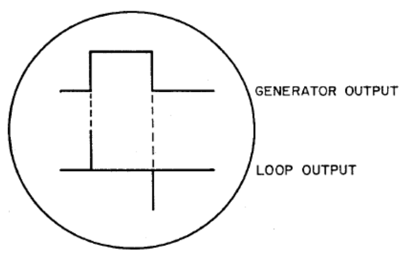

Figure 2.

3.2 Noise Source Tracing

1. Connect the function generator to the circuit shown in Figure 3. Make a second square pickup loop and connect to the scope input that was connected to the generator output. Use coax: cable (50 ohm) and a 50 ohm termination as was used for the first loop. Adjust the scope sensitivity for best viewing. If the trace goes off screen during the experiment, reduce the sensitivity as appropriate.
2. Place one loop (fixed loop) next to the grid as shown in Figure 4 and trigger on this waveform. Move the second loop (movable loop) along the bottom of the grid. Note the phase reversal on the trace associated with the moving loop as the loop passes the branch containing the "noise" source.

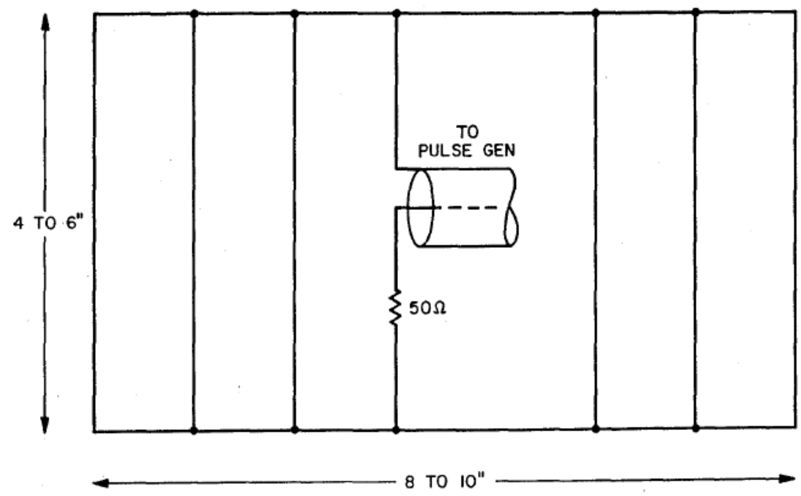

Figure 3.

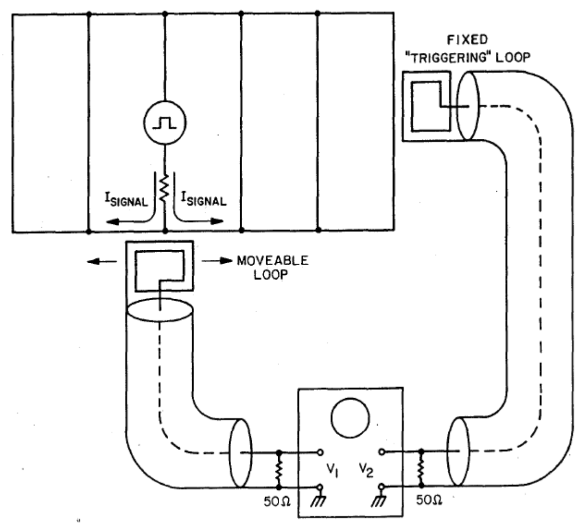

Figure 4.

4. Theory

The voltage induced in the pickup loop is

$$v_{induced} = NM\frac{di}{dt}$$

where i is the current in the signal path, N is the number of turns of the pickup loop, and M is the mutual inductance between the pickup loop and the loop carrying the current. Therefore, the waveshape of the voltage induced into the pickup loop is equal to the derivative of the current in the signal path as shown in Figure 3. Thus the induced voltage of the measurement loop is related to the slope (rise or fall time) of the current waveform.

The sign of the mutual inductance M depends on the relative orientation of the pickup loop and the loop carrying the current i. This is because the magnetic flux caused by the current i forms concentric circles around i with the direction of this flux given by the right-hand rule. The flux threads the area formed by the measurement loop and induces a voltage in that loop (the measured voltage). The polarity of this induced voltage is determined by Lenz's law[l]. If either (1) the loop is rotated 180 degrees, or (2) the current direction is reversed, the polarity of the measured voltage will reverse. In Figure 4, moving the measurement loop from left to right causes the magnetic flux from the (signal) current that threads the loop to reverse polarity and hence the induced voltage reverses polarity.

The interference potential of currents is related more to the pulse rise/fall times than to the repetition rate of the pulse train. Increasing rise/fall time can have a direct correlation with reduced noise emissions. Since the magnitude of the voltage induced in the pickup loop is directly related to pulse rise/fall times, this indirect sampling method can be used to see whether circuit modifications have resulted in increased rise/fall times.

Another application would be to find a source of noise in a system. Consider the generator in the circuit of Figure 4 to be a noisy IC (possibly caused by an open decoupling capacitor) pumping noise currents onto the ground system. If the loop is moved along the bottom conductor in Figure 4, the branch containing the noisy IC can be detected by the phase reversal of the pickup voltage when that branch is passed.

5. References

1. C.R. Paul and S.A. Nasar, Introduction to Electromagnetic Fields, McGraw-Hill, Second edition, 1987.

Crosstalk in Cables

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1. Objective

To understand the mechanism of crosstalk in which the electromagnetic fields of electrical signals on one pair of wires in a cable bundle couple to and induce signals in another pair of wires. To investigate the factors that influence the coupling and methods for reducing the crosstalk.

2. Equipment

- Sinusoidal oscillator (1 kHz to 1 MHz) with 50 ohm source impedance and at least 20V p-p open-circuit voltage.
- Function or pulse generator capable of producing 100 kHz pulse trains having rise/fall times of 1 μs or less and an open-circuit voltage of 5V p-p.
- Dual trace oscilloscope (at least 50 MHz bandwidth).
- Cables
    - Standard appliance cord (10').
    - RG-58 coaxial cable (5').
    - Two 6' lengths of insulated hookup wire (20 to 24 gauge).
- Four 10 ohm carbon resistors (1/4 watt).

3. Procedure

3.1 Crosstalk in Unshielded Wires

1. Place two 5' lengths of appliance cord flat on a nonmetallic table and tape them together so that the insulations are touching as shown in Figure l(a).
2. Solder the 10 ohm resistors to the ends of these cords as shown in Figure l(a).
3. Attach the oscillator to one cord, and one channel of the oscilloscope to measure V_1.
    a. Adjust the frequency of the oscillator to 1 kHz and the output level at V_1 to 3Vp-p.
    b. Attach the other channel of the oscilloscope to the other cord (across the 10 ohm resistor) to measure V_2.
    c. Repeat the measurements at frequencies of 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0 and 9.0 in each decade up to 1 MHz.
    d. Increase the oscillator frequency until you get a V_2 that is measureable.
4. Plot the interference voltage transfer ratio; V_2/V_l at the above frequencies on 3 cycle log-log graph paper.
5. Repeat the above experiment with the two appliance cords parallel but separated by 1/2 inch.
6. Replace the sinusoidal oscillator with the function generator set to produce a 100 kHz square wave with a peak voltage of 0.5 V and a pulse rise/fall time of 1 microsecond.

7. Sketch V_1 and V_2 versus time and note the effect on V_2 of changing the rise/fall time of V_1. Observe that the level of V 2is directly dependent on the rise/fall time of V 1; the shorter the rise/fall time of V_1 the larger the amplitude of V_2.

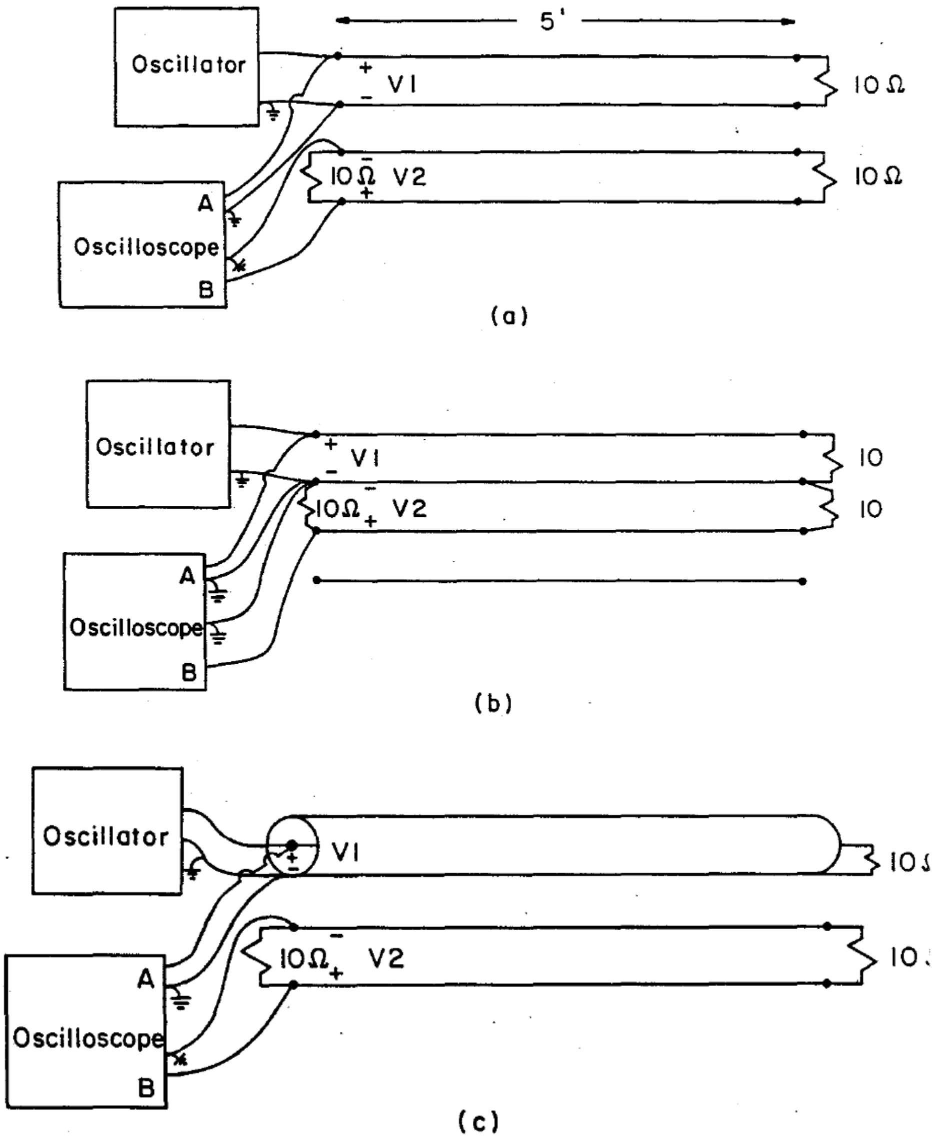


Figure 1.

3.2 Crosstalk by Common Impedance Coupling

1. Repeat 3.1 for the configuration shown in Figure l(b). The two appliance cords are to remain taped together as in 3.1, step 1. Simply resolder two 10 ohm resistors between both ends of one wire of each pair of cords.

3.3 Crosstalk in Shielded Cables

1. Replace the driven pair of wires with a 5 foot length of RG-58 coaxial (shielded) cable as shown in Figure 1 (c).
2. Repeat 3.1 steps 3 - 7 for this configuration.
3. Replace the coaxial cable with the pair of insulated hookup wire and twist these two wires together to give about one twist every three inches.
4. Repeat 3.1 steps 3 - 7 for this configuration.

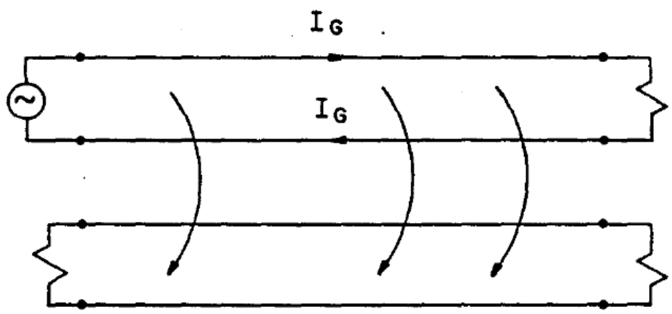
4. Theory

4.1 Crosstalk in Unshielded Wires

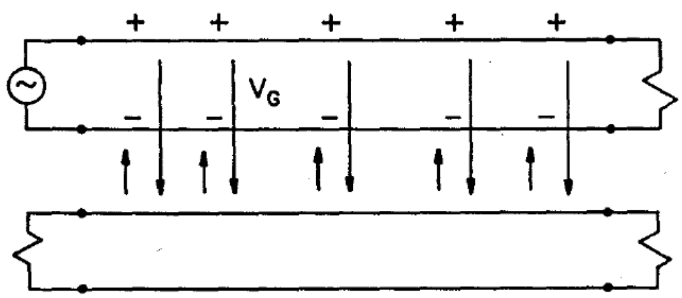
Currents and voltages associated with signal transmission on a pair of parallel wires (the generator wires) generate electric and magnetic fields in the vicinity of those wires. These electromagnetic fields interact with any neighboring wires (the receptor wires) and induce voltages and currents into these lines as shown in Figure 2. Portions of these induced signals appear at the ends of the receptor wire circuit. This unintentional coupling of signals from one circuit to another can cause the devices at the ends of the receptor wires to be interfered with and thus their performance can be degraded. This is commonly referred to as crosstalk. This crosstalk is due to two mechanisms. The current of the generator line produces a magnetic field that is coupled to the receptor line by the mutual inductance, L_m, between the two circuits. This is referred to as inductive coupling. Similarly, the voltage of the generator line produces an electric field that is coupled to the receptor line by a mutual capacitance, C_m, between the two circuits. This is referred to as capacitive coupling. Both mutual impedances are functions of the cross-sectional dimensions of the lines such as wire radii, and wire separation. Separating the two lines reduces the mutual impedances. Both L_m and C_m are direct functions of the line length; doubling the line length doubles the crosstalk, V_2. The crosstalk also varies directly as the frequency of the signal on the generator line; the higher the frequency the higher the crosstalk. Thus for the experiment shown in Figure 1(a), the magnitude of the output voltage should be [1,2,3]:

$$V_2 = fK(L_m)LI_1 + fK(C_m)LV_1 \quad (1)$$

where I_1 and V_1 are the current and voltage of the generator line, L is the line length, f is the frequency of I_1 and V_l, and $K(L_m)$ and $K(C_m)$ are the inductive and capacitive coupling coefficients, respectively, for the particular cross-sectional configuration. Note that the crosstalk should increase linearly with frequency. This should show up on your graphs as a line with a slope of 20 dB/decade. Normally, one component of the coupling will dominate the other. For small terminal resistances where currents and magnetic fields are large, the inductive coupling will be larger than the capacitive coupling. For large terminal resistances where the voltages and electric fields are large, the situation is reversed.



(a) Magnetic Field Coupling (Inductive)



(b) Electric Field Coupling (Capacitive)

Figure 2.

2. Time-domain crosstalk is also due to this mutual inductance and mutual capacitance between the two circuits. The time-domain voltage induced across the load of the receptor line, $v_2(t)$, is [2,3]

$$v_2(t) = \frac{1}{2\pi} K(L_m) \frac{di_1(t)}{dt} L + \frac{1}{2\pi} K(C_m) \frac{dv_1(t)}{dt} L \quad (2)$$

Note that the induced voltage is proportional to the time-derivative (slope) of the current and voltage waveforms in the generator circuit. Typical waveforms resemble trains of triangular-shaped pulses as shown in Figure 3. So the induced crosstalk voltage resembles pulses occurring during the rise/fall times of the driven line voltage. The heights of the pulses are proportional to the slope of these transitions on the generator line.

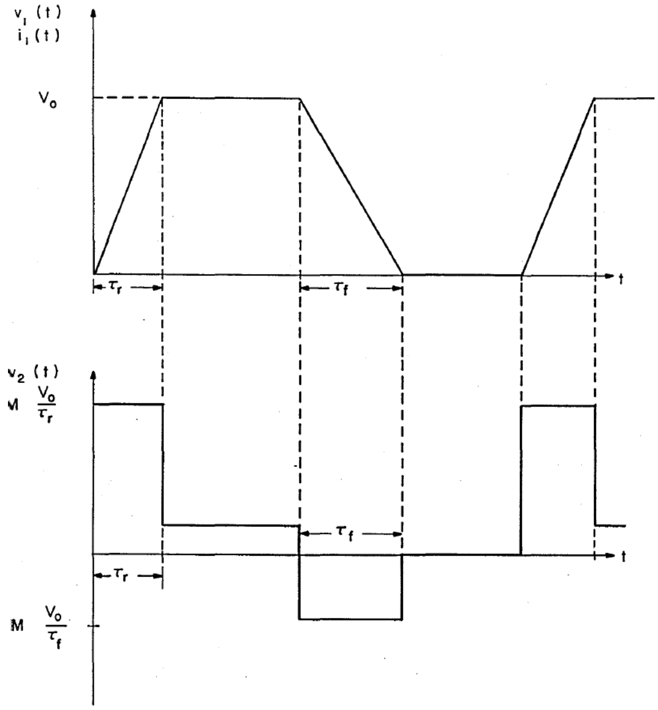


Figure 3.

4.2 Crosstalk by Common Impedance Coupling

1. Whenever two currents share a common return path, the current of this desired signal passing through this impedance of the return path develops a voltage across the common impedance that appears directly in the receptor circuit [21. For the case shown in Figure 1(a), the two circuits do not share a common return path. However, suppose we wished to (,save wire" and choose to have both circuits share one of the wires as a common return. This configuration is shown in Figure 1(b).

In the case of Figure 1(b), the common impedance consists of one of the wires of the appliance cord. This configuration is modeled as shown in Figure 4(a). Each wire of the appliance cord consists of 41 strands of #34 gauge wire. From reference [2] each strand has a resistance of 0.2609 ohms/foot. The total resistance of each wire consists of 41 of these strands in parallel or

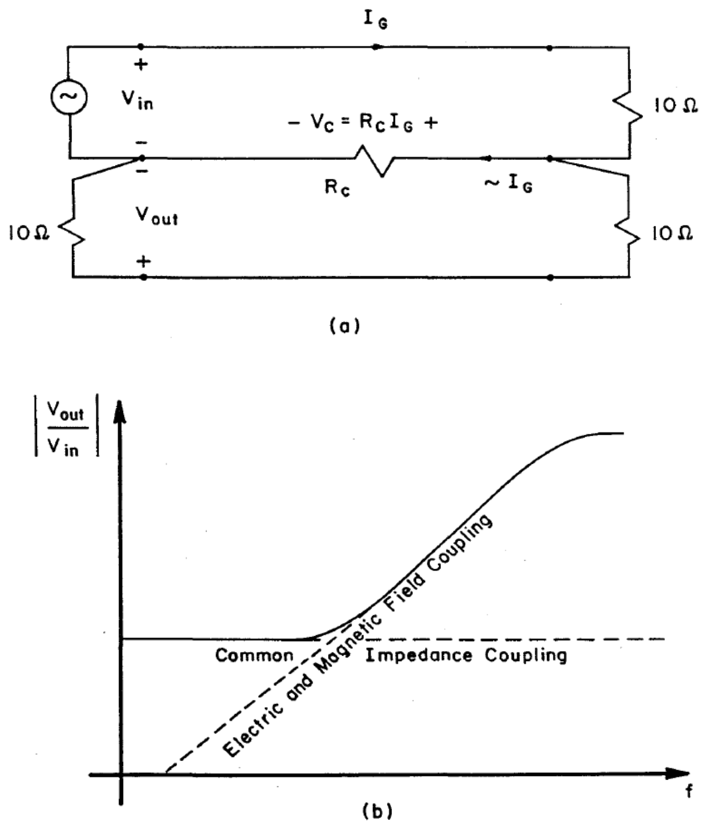


Figure 4.

0.00636 ohms/foot. For a 5-foot length, the total resistance of this common path is 0.0318 ohms. The voltage developed across this common impedance is:

$$V_c = R_c I_G \qquad (3)$$

which is equal to 9.6 mV p-p in this case. This voltage is divided across the two 10 ohm resistors of the receptor circuit as shown in Figure 4 by voltage division to give:

$$V_2 = V_c / 2 = 4.8 \text{ mV (p-p)} \qquad (4)$$

For the configuration shown in Figure 1(b), the magnitude of the output voltage is again given by Equation (1) but the coupling coefficients are different than for Figure 1(a).
As the frequency of the signal is decreased, the combined electric and magnetic field coupling will decrease at a rate of 20 dB/decade until it reaches this "floor" produced by common impedance coupling. As the frequency is further reduced, the crosstalk will remain at this level due to co=on impedance coupling even as the frequency is reduced to DC !. (See Figure 4(a).)
2. Time-domain crosstalk involving common-impedance coupling is similar to the previous case (time-domain crosstalk not involving common-impedance coupling) with the addition of a constant level between the rise and fall times of the pulse. Between the rise and fall times, the input voltage appears virtually constant at V 0 (see Figure 3) so that

$$v_2(t) = V_c / 2 = 0.8 \text{ mV} \qquad (5)$$

where the voltage across the common impedance is

$$v_c(t) = R_c \frac{v_1(t)}{10} = 1.6mV \qquad (6)$$

The total time-domain crosstalk voltage is the superposition of (2) and (5).

4.3 Crosstalk Reduction Techniques

1. Replacing the pair of wires of the generator line with a coaxial cable as shown in Figure 1(c) can reduce the crosstalk. The shield tends to confine the electric field to its interior, thus reducing the electric field coupling. Also the generator line currents are essentially located on the same axis, but are equal and oppositely directed. Thus the effect of the magnetic field is canceled in the vicinity of the receptor circuit [1, 2].
2. Because the effects of the electric and magnetic fields from adjacent twists tend to cancel in the vicinity of the receptor circuit, twisting a pair of wires together will have the effect of cancelling the fields caused by the voltage and currents on those wires [2]. Thus the crosstalk induced in a nearby receptor circuit will be reduced.

5. References

1. Ott, H.W., Noise Reduction Techniques in Electronic Systems, John Wiley & Sons, 2nd Edition, 1988.
2. C.R. Paul, Introduction to Electromagnetic Compatibility, John Wiley & Sons, NY, 1992.
3. Paul, C.R., "Printed Circuit Board Crosstalk", 1985 IEEE International Symposium on Electromagnetic Compatibility, Wakefield, Mass., August, 1985.

Ground Noise in Digital Logic

Henry W. Ott
Henry Ott Consultants

1. Objective

To demonstrate the ground noise voltage generated by a single TTL logic signal flowing through a signal return conductor, and how it depends on the characteristics of the conductors and their physical configuration.

2. Equipment

- TTL compatible crystal clock oscillator (any frequency between 2 and 10 MHz.).
    - For example, a Motorola K1100A at 6 MHz.
- Two 7400 (or 74LS00), quad two input NAND gate IC's.
- A 4.5 to 5.5 volt battery.
- Two 6 inch lengths of #18 gauge solid copper wire.
- Miscellaneous hookup wire.
- A vector board or breadboard to mount the circuits on.
- Oscilloscope with a bandwidth greater than 50 MHz.
- The following equipment is needed for the additional optional experiments listed below.
    - Two 6 inch lengths of #12 gauge bare copper wire.
    - Two 6 inch lengths of #24 gauge bare copper wire.
    - A 6 inch length of coaxial cable.

3. Procedure

3.1 Construction
Using the materials listed above, construct the circuit shown in Figure 1. Use the two 6 inch lengths of #18 gauge wire to form a transmission line between the two 7400 IC's. Arrange the circuit such that the 18 gauge signal conductor can be moved to vary the spacing between it and the ground conductor from 1/8 inch to 3/4 inch.

3.2 Ground Noise Voltage
1. Space the 18 gauge signal and ground conductors 3/4 inch apart. Using the oscilloscope, measure the peak-to-peak voltage between two points, 4 inches apart, 2 inches apart, and 1 inch apart on the ground conductor.
2. Move the oscilloscope leads until they are 2 inches apart on the ground conductor and re-measure the voltage. Measure the voltage with the leads 1 inch apart.
3. Space the 18 gauge signal and ground conductors 1/8 inch apart. Using the oscilloscope, measure the voltage between two points, 4 inches apart, on the ground conductor.

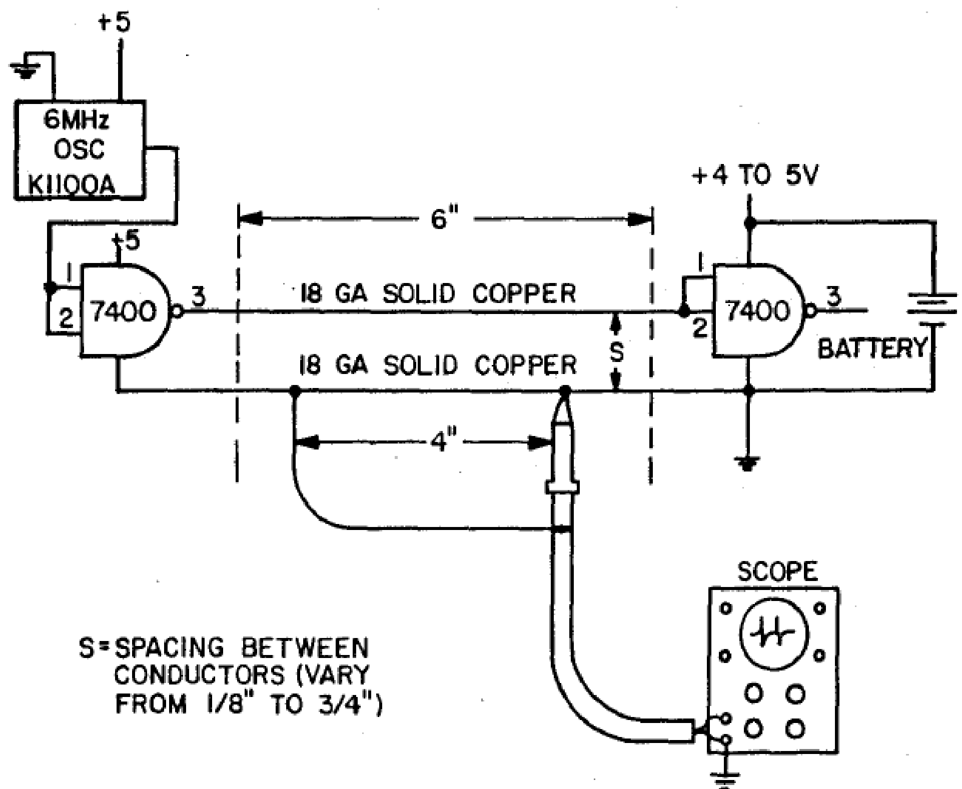


Figure 1.

3.3 Additional (Optional) Experiments
1. Replace the 18 gauge conductors with 12 gauge conductors (twice the diameter of 18 gauge) and repeat the above measurements.
2. Replace the 18 gauge conductors with 24 gauge conductors (half the diameter of 18 gauge) and repeat the measurements.
3. Replace the 18 gauge conductors with a 6 inch long coaxial cable. Make the shield terminations as short as possible. Measure the noise voltage between two points on the shield that are 4 inches apart.

4. Theory

In order to minimize the ground noise voltage generated by the switching transients of digital logic the impedance of the signal return path must be minimized. In the case of digital logic, the frequencies of concern are not just the fundamental frequency of the signal but more importantly its harmonics. The square wave produced by a TTL logic gate has considerable energy content in the 10 to 100 MHz region. At these frequencies, it is the inductance of the signal return conductor that is most important. If signal return circuit impedance is to be minimized, the inductance must be minimized.

In order to reduce the inductance we must understand its dependence on the physical properties of the conductors. Inductance is a function of the natural logarithm of the conductor diameter. Due to this "log" relationship, it is difficult to achieve a large decrease in inductance by increasing the conductor size. In a typical case, doubling the diameter (an increase of 100%) will only decrease the inductance by about 20% [1]. Whenever possible, advantage should be taken of this effect, even if it is relatively small. If a large decrease in inductance is required, however, some other method of reducing inductance must be found.

As demonstrated in this experiment, inductance and therefore noise voltage is directly proportional to the length of a conductor. We can take advantage of this by minimizing the lengths of critical leads. For example, those carrying large transient currents such as clock leads. This is not a universal solution however, since some leads must be long in a system.

Another important method of reducing inductance, demonstrated by this experiment, is to minimize the area of the loop enclosed by the current flow. Two conductors carrying current in opposite directions (such as the Signal and ground leads) have a total inductance L equal to

$$L = L_1 + L_2 - 2L_m$$

where L_1 and L_2 are the self-inductances of the two individual conductors and L_m is the mutual inductance between them. In order to minimize the total inductance of the complete current path, the mutual inductance between the conductors must be maximized. Therefore, the two conductors should be placed close together (minimum area between them).

If the coefficient of magnetic coupling between the two conductors were unity, the mutual inductance would equal the self inductance and the total inductance of the closed loop would be zero. At high frequencies a coaxial cable approaches this ideal condition. Placing forward and return current paths close together, therefore, is a very effective method of reducing inductance. This can be accomplished by using a tightly twisted pair of a coaxial cable.

Additional information on the concept of digital grounds can be obtained from reference [2].

5. References

1. Ott, H.W., Noise Reduction Techniques in Electronic Systems, Page 128, Table 5-3, John Wiley & Sons, 2nd Edition, 1988.

2. Ott, H.W., "Digital Circuit Grounding and Interconnection", 1981 IEEE International Symposium on Electromagnetic Compatibility.

Electromagnetic Leakage Through Seams

Richard J. Mohr
R. J. Mohr Associates, Inc.

1. Objective

To show a means of measuring leakage of electromagnetic energy through the seams of an enclosure to characterize the effects of various seam treatments.

2. Equipment

- Shielded enclosure with removable cover, preferably with at least 8 threaded fasteners.
- Coaxial panel jacks with extended center conductor – Qty 2.
- Spring contact.
- Signal generator operable to at least 1 MHz. The generator should preferably have a low output impedance (50Ω) and be capable of delivering at least 1 V to a matched load.
- Receiver or spectrum analyzer tunable to the frequency of the signal generator. The generator should preferably have a sensitivity of 1 μV (-107dBm for a 50W receiver), or better.

3. Procedure

3.1 Preparation of Test Sample

1. Secure one (1) coaxial panel jack (Item B) to the test enclosure (Item A) as indicated in Figure 1(a).
2. Solder spring contact to center conductor of connector so it will contact the cover when the cover is fastened to the enclosure as indicated in Figure l(a).
3. Prepare the second coaxial panel jack (Item B) to function as a voltage probe. This will require providing an extension from the connector shell to function as a ground reference connection. With a flanged connector, this may be achieved by securing a threaded fastener to the flange as shown in Figure l(b).
4. Secure cover to enclosure.
5. With a grease pencil, number sequentially each fastener position and location between fasteners around the periphery of the cover.

3.2 Measurements

1. Set the signal generator (Item D) to the first test frequency, say 1MHzj record on data sheet.
2. Set output level of the generator to a convenient level, say 1 V into 50Ω.
3. Connect the generator to the connector on the test enclosure.
4. Connect the receiver (Item E) to the voltage probe prepared in para. 3.1, Step 3.
5. Tune the receiver to the frequency of the signal generator.
6. Place the voltage probe so as to measure the potential difference between the cover and the enclosure at Test Position 1. Note, the center conductor of the coaxial connector contacts the cover while the reference probe contacts the enclosure.

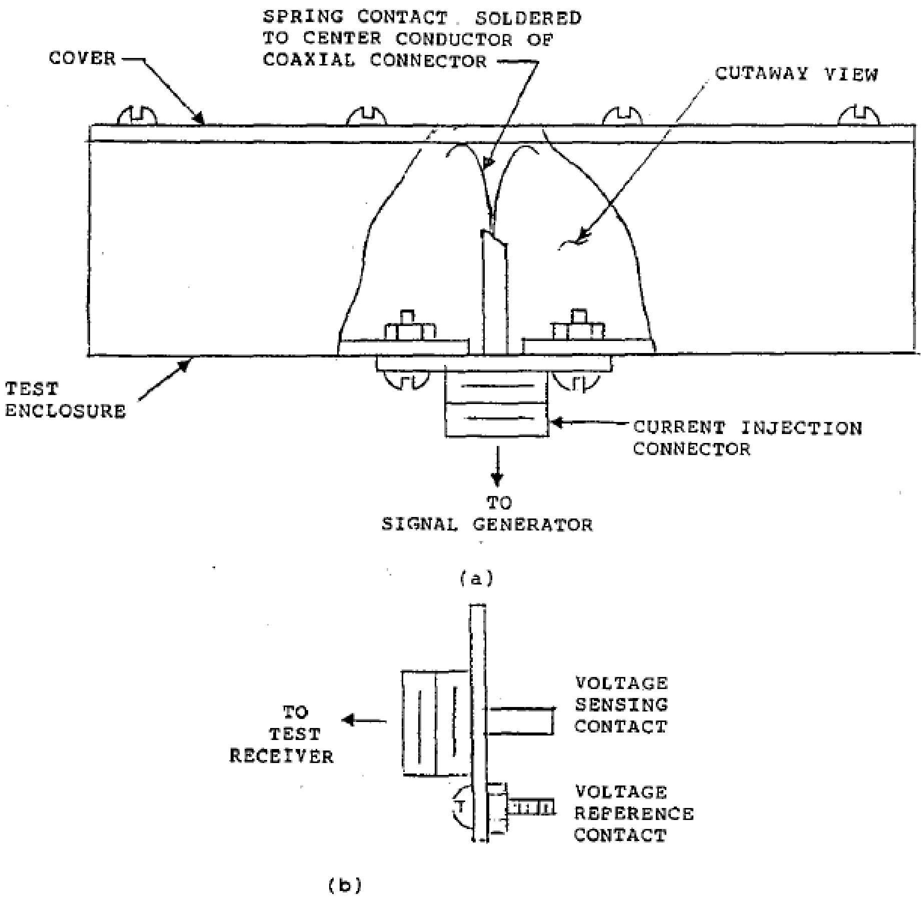


Figure 1. (a) Test Enclosure, showing mounting of Current-Injection connector.
(b) Voltage Probe, showing implementation of a Reference Contact

7. Record the measured voltage and probe position on the data sheet.
8. Repeat Steps 6 and 7 at each numbered measurement position.
9. Repeat Steps 2 – 8 at other frequencies, say 3 MHz and 10 MHz.
10. Vary the seam treatment and repeat Steps 1-9. Typical variations may include:
    - different securing torque on the fasteners
    - reduced number of fasteners
    - buffed seam interface (with steel wool or fine emery cloth)
    - use of conductive gaskets.

3.3 Data Analysis

Plot the measured voltage vs. probe position as in Figure 2. The lower voltages indicate a better EMI seam. Note the variation of voltage vs. measurement position, frequency, number of fasteners, fastening torque, etc.

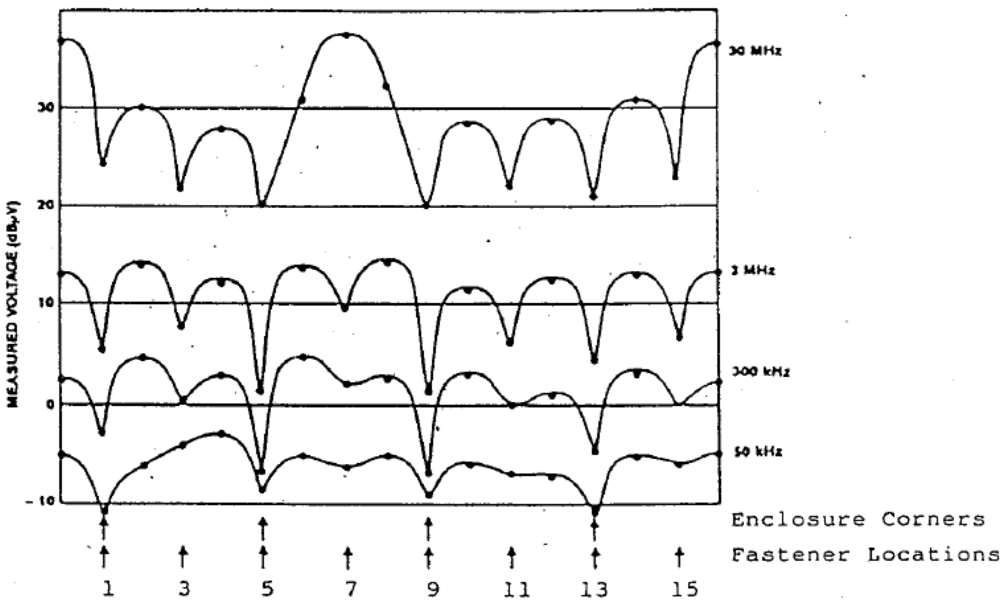


Figure 2. Sample Data Plots.

4. Theory

Electromagnetic leakage via seams in shielded enclosures occurs primarily as a result of currents which cross the seam. Such crossings cause a voltage to appear on the far side of the seam; electromagnetic leakage via the seam is directly proportional to this (transfer) voltage. In shielding theory the seam is characterized in terms of its transfer impedance as follows:

$$Z_T = V/J \qquad (1)$$

where,

Z_T = Transfer Impedance of seam (Ohm-meters)
V = Transfer Voltage
J = Density of current which crosses the seam (A/m)

Seam transfer impedance is conventionally expressed in the dimensions of microohm-meters and typically ranges in value from 1 to 3000 µOhm-meters. The lower values are achieved in seams which employ wide-area metal-to-metal contact with close fastener spacings and/or with the use of effective EMI gaskets.

The data (and plots prepared per para. 3.3) will show that the transfer voltage is not constant around the cover. This is partly because the exciting current density is not uniform (less at the corners of the enclosure) but mostly because the transfer impedance is not uniform around the enclosure (lower in proximity to the fasteners).

As an optional exercise, estimate the average transfer impedance of the seam. This may be made by dividing the average measured transfer voltage by the average current density. The average current density can be determined by taking the ratio of the current injected into the enclosure, to the periphery of the seam. The current injected into the enclosure is essentially the short-circuit current of the generator (use Thevenin's Theorem to determine this).

The Effect of Penetrating Conductors on Enclosure Shielding

John G. Kraemer
Rockwell Collins

1. Objective

Illustrate how penetrating conductors degrade the shielding effectiveness of shielding enclosures.

2. Equipment

- Electronic equipment item with metal chassis. A desktop computer without peripherals attached would be a good candidate. Only the power cord is needed (it is a filtered penetration).
- Spectrum analyzer with remote display and display recording capabilities
- Active indoor VHF/UHF DTV antenna with coax cable and adaptors to spectrum analyzer
- 1.15 meter stiff 14 or 16 AWG insulated wire with insulation over each end

3. Procedure

1. Setup up the equipment as shown in Figure 1. With the electronics unit unpowered, measure and record the radiated emissions in the 180 to 800 MHz frequency range. Identify and note the emissions from local TV stations and radio services.
2. Power the electronics unit. Measure and record the radiated emissions in the 180 MHz to 800 MHz frequency range. Note the levels and frequencies of the new emissions and compare to that of the local TV stations and radio services.
3. Carefully insert 15 cm of the wire into a vent hole. Measure and record the radiated emissions in the 180 MHz to 800 MHz frequency range. Note the levels and frequencies of the new emissions and compare to that of the local TV stations and radio services. Also note how much the level of the emissions found in step 2 increased. For voltage, 20 dB = 10x, 40 dB = 100x.
4. Carefully remove the insulation on the inserted wire at the point of penetration. Using wood or plastic pencil, force the bare section of the wire to contact the chassis at the vent hole. Measure and record the radiated emissions in the 180 MHz to 800 MHz frequency range. Explain why the emissions from the equipment item and power cord are notably less than the case with the insulated wire inserted and not bonded to the chassis at the point of penetration.
5. Note the emissions from the equipment item and power cord.

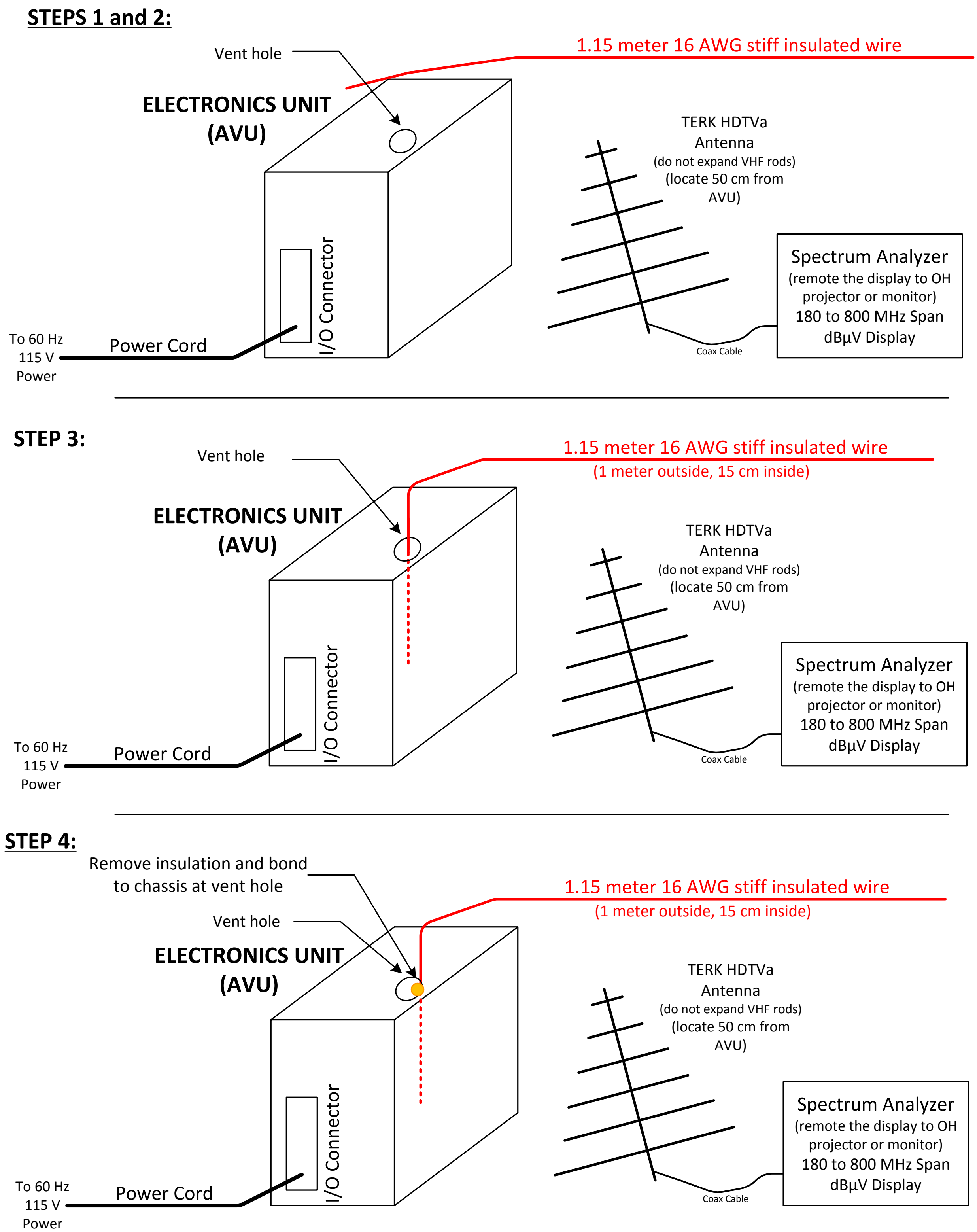

STEPS 1 and 2:
Vent hole
1.15 meter 16 AWG stiff insulated wire
ELECTRONICS UNIT (AVU)
TERK HDTVa Antenna (do not expand VHF rods) (locate 50 cm from AVU)
Spectrum Analyzer (remote the display to OH projector or monitor) 180 to 800 MHz Span dBµV Display
I/O Connector
To 60 Hz 115 V Power
Power Cord
Coax Cable
STEP 3:
Vent hole
1.15 meter 16 AWG stiff insulated wire
(1 meter outside, 15 cm inside)
ELECTRONICS UNIT (AVU)
TERK HDTVa Antenna (do not expand VHF rods) (locate 50 cm from AVU)
Spectrum Analyzer (remote the display to OH projector or monitor) 180 to 800 MHz Span dBµV Display
I/O Connector
To 60 Hz 115 V Power
Power Cord
Coax Cable
STEP 4:
Remove insulation and bond to chassis at vent hole
Vent hole
1.15 meter 16 AWG stiff insulated wire
(1 meter outside, 15 cm inside)
ELECTRONICS UNIT (AVU)
TERK HDTVa Antenna (do not expand VHF rods) (locate 50 cm from AVU)
Spectrum Analyzer (remote the display to OH projector or monitor) 180 to 800 MHz Span dBµV Display
I/O Connector
To 60 Hz 115 V Power
Power Cord
Coax Cable

Figure 1.

4. Theory

Electromagnetic (EM) fields from a radiating source can induce currents onto a conductor. This current will continue to flow on the conductor as it penetrates the shield boundary. The radiating source of energy can be inside the enclosure, or it can be outside the enclosure. (This demo involves the case where the radiating source is inside the enclosure.) The current flowing on the conductor will cause the production (re-radiation) of an EM field on the other side of the shielding boundary; the wire is analogous to an antenna.

The wire in the demonstration could represent a power input line, a signal I/O line, the shield over a shielded wire (coax), or the outer shield (overbraid) of a cable bundle. Products have limits on radiated emissions from the equipment item and associated wires and cables. Excessive emissions could result in interference to on-board radio communication and navigation receivers via reception of the emissions by the radio's antenna. Equipment, with associated cables and wires attached, has the requirement to be immune to radiated electromagnetic fields from the environment it will be used in. Shielding from the equipment chassis is typically needed to allow EMI compliance and system level EMC in the defense/aerospace electronics sector. Termination of penetrating conductors at the shielding boundary must be considered as part of the electrical and mechanical design of the equipment. If the penetrating conductor is a signal or power conductor, "termination at the boundary" is done with an EMI filter.

Consider termination of all penetrating conductors at the shield boundary. If a signal or power conductor is enclosed by a shield, terminate the shield at the boundary. Unshielded signal and power conductors are terminated at the shield boundary via an EMI filter; the low pass EMI filter allows signal and power to pass, but diverts high frequency energy to the shield boundary. Cable and wire shields are typically bonded directly to the shield at the boundary.

Effect of Pulse Rise/Fall Time on Signal Spectra

Clayton Paul
University of Kentucky, Dept. of Electrical Engineering

1. Objective

To investigate the effect of pulse rise/fall times on the frequency (spectral) content of typical periodic clock signals. To show that pulses having short rise/fall times have frequency spectral content that extends to higher frequencies than do pulses having longer rise/fall times. To investigate the effect of lead inductance on the performance of circuit elements such as capacitors.

2. Equipment

- Oscilloscope (with 100 MHz bandwidth) and a 50Ω plugin.
- Spectrum Analyzer capable of sweeping to 100MHz.
- DIP oscillator capable of producing a trapezoidal pulse train having a repetition rate of a few MHz. A suggested type is a Dale XO-338 4 MHz oscillator fitting a 14-pin socket.
    - Note: Pin 14 is for +5V DC, pin 7 is ground and the output is between pin 8 and pin 7. Pin 1 is unused.
- A length of 50Ω coaxial cable. A 2-foot length is sufficient.
- Two female banana plug panel mounts.
- One l8-pin DIP socket for the oscillator.
- One piece of "perf board" with holes on 100mil centers for mounting the components. A dimension of 5cm x 5cm is sufficient.
- One DC power supply capable of producing 5V.
- Two 500pF ceramic capacitors.
- One female BNC panel mount connector.

3. Procedure

3.1 Construction of device

1. Mount the BNC panel mount connector, the two banana panel mount plugs, and the 18-pin DIP socket on the "perf-board" as shown in Figure 1. Keep all components close together.
2. Solder a connection wire between the +5 banana plug and pin 18 of the DIP socket. Solder a connection wire between the ground banana plug and pin 7 of the DIP socket. Solder a connection wire between pins 7, 8, 9 of the DIP socket and the ground of the BNC panel mount connector. Solder a connection wire between pins 10, 11, 12 of the DIP socket and the center pin of the BNC panel mount connector.
3. Insert the oscillator in the first 14 pins of the DIP socket. Pin 1 of the oscillator should go in pin 1 of the socket, pin 7 of the oscillator should go in pin 7 of the socket, pin 8 of the oscillator should go in pin 12 of the socket, and pin 14 of the oscillator should go in pin 18 of the socket. Pins 8, 9, 10, 11 will be used to place the capacitors in parallel with the oscillator output (and the 50Ω input resistance of the oscilloscope/spectrum analyzer).

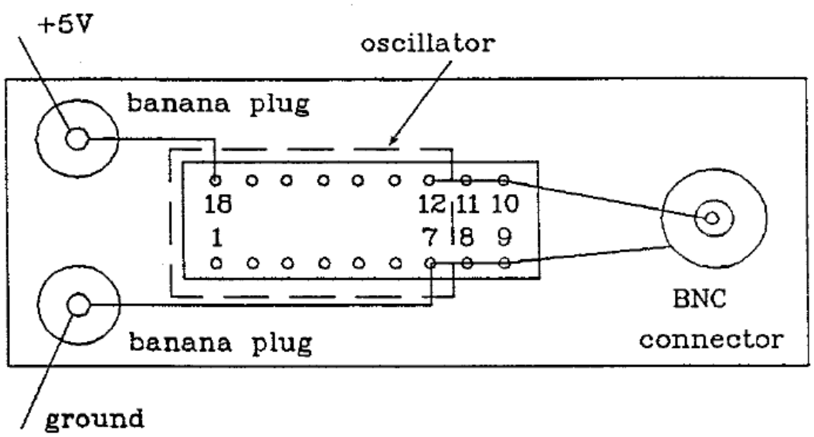


Figure 1. The experimental device.

3.2 Effect of rise/fall time on spectral content

1. Attach the 5V DC power supply to the banana plugs of the device. Connect the output of the device to the 50Ω plugin input of the oscilloscope with the coaxial cable. Measure the peak level of the pulse waveform (should be about IV). Measure the rise/fall times of the pulse (10%-90%). These should be about 10ns.

2. Connect the output of the device to the spectrum analyzer which is sweeping to 100MHz. Insure that enough attenuation is selected for the spectrum analyzer so as not to overload it (normally 30dB is sufficient). Measure the levels of several harmonics. If a 4MHz oscillator is used, measure the levels of the 11th (44MHz), 17th (68MHz), and 19th (76MHz) harmonics. (Typical levels are 92dBμV, 84δBμV, 80dBμV.)

3. Repeat steps 1 and 2 with a 500pF capacitor inserted into pins 9 and 10 of the socket. This places the capacitor in parallel with the 50Ω of the input to the oscilloscope/spectrum analyzer and so rolls off the frequency response of the load impedance for the oscillator. Cut the lead lengths to as short as possible. (Typical rise/fall times are 40ns and 25ns. Typical measured levels are 74dBμV, 56dBμV, and 44dBμV).

4. Repeat steps 1 and 2 with a 500pF capacitor having lead lengths of 1/2 inch inserted into pins 9 and 10 of the socket. This illustrates the effect of lead inductance. (Typical rise/fall times are 40ns and 25ns. Typical levels are 66dBμV, 62dBμV and 63dBμV.) Observe that the longer leads of the capacitor cause the spectral content to increase over that with short leads.

5. Repeat steps 1 and 2 with the short-lead-length capacitor in pins 9 and 10 and the long-lead-length capacitor in pins 8 and.11. This gives (ideally) 1000pF across the oscillator output and further reduces the rise/fall times and spectral content. (Typical rise/fall times are 80ns and 20ns. Typical measured levels are 68dBμV, 60dBμV and 44dBμV. Observe that even though the rise time is significantly reduced, the fall time is not substantially reduced. Also the high-frequency spectral content (above 50 MHz) is still quite large.)

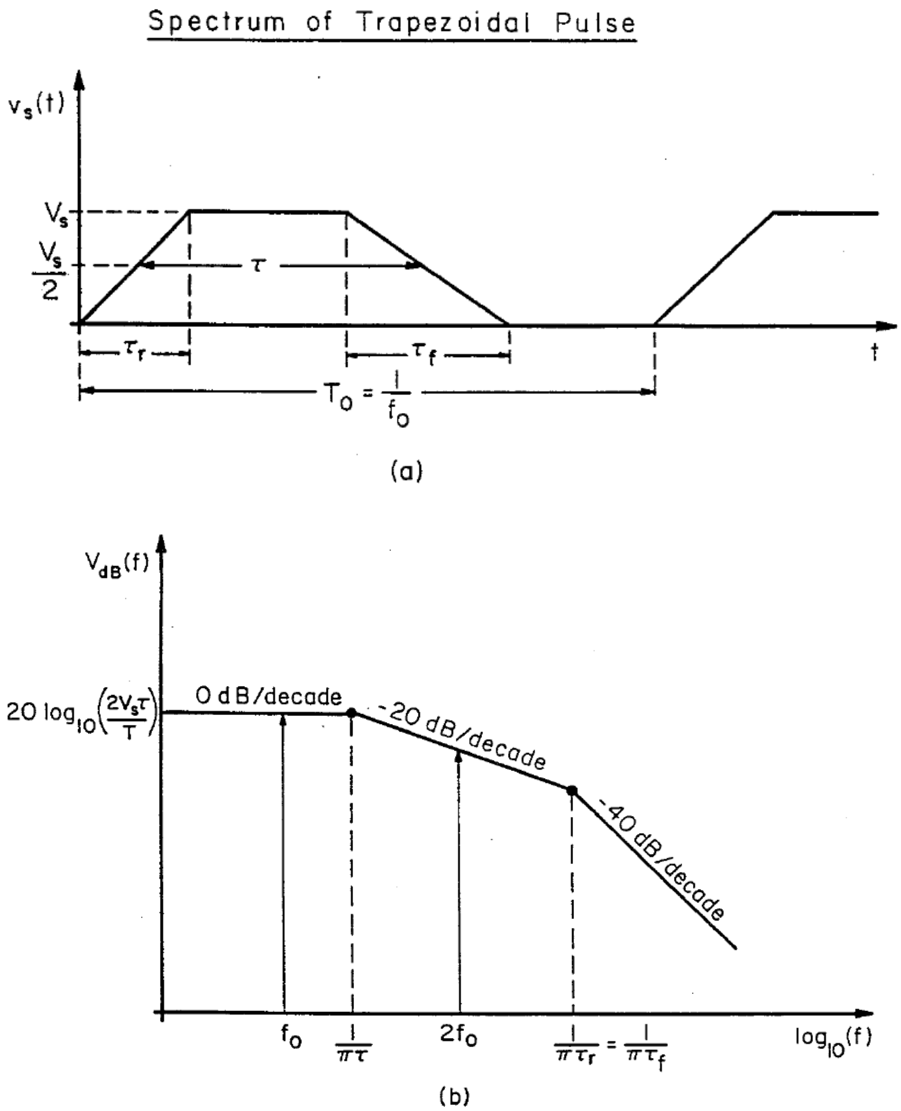


Figure 2. A trapezoidal pulse train representing clock signals.
(a) The time-domain signal, (b) the frequency-domain spectrum

4. THEORY

1. Consider the trapezoidal pulse train shown in Figure 2(a). The pulse width, τ, is between the 50% levels of the pulse. The pulse rise time is denoted by τ_r and the fall time is denoted by τ_r. This waveform is representative of typical clock (and to some degree, data) signals in digital products. Since it is a periodic waveform with period T and repetition frequency $f_o = 1/T$, it can be expanded in a Fourier series [1, 2]. The series consists of sinusoidal components at multiples (harmonics) of the base frequency, f_o. The amplitudes of these components can be obtained [1]. However, unless the rise and fall times are equal, $\tau_r = \tau_f$, the result is complicated. If we assume $\tau_r = \tau_f$ a simple result for the amplitudes of the spectral components is obtained [1]:

$$\left|c_n\right| = 2A\frac{\tau}{T}\left|\frac{\sin\left(n\pi\tau / T\right)}{n\pi\tau / T}\right|\left|\frac{\sin\left(n\pi\tau_r / T\right)}{n\pi\tau_r / T}\right| \quad \tau_r = \tau_f \tag{1}$$

This result can be bounded as shown in Figure 2(b) [1]. The bounds on an asymptotic or Bode plot consist of a 0 dB/decade part extending to $l/\pi\tau$, a -20dB/decade part extending to $1/\pi\tau_r$ and a -40dB/decade part after that. Observe that the high-frequency spectral content is primarily governed by the second break point, $l/\pi\tau_r$. So increasing the pulse rise (and fall) times (making them longer) moves this second break point down in frequency and causes more of the high-frequency spectral components to roll off at -40dB/decade rather than -20dB/decade. Reducing the high-frequency spectral content of a signal is an important and effective way of reducing the potential EMC problems caused by this signal.

2. One way of "rolling off" the pulse rise/fall times is to place a capacitor in parallel with the signal output. In the above experiment, the 500pF capacitor is placed across and in parallel with the 50Ω of the oscilloscope/spectrum analyzer. This causes the high-frequency impedance seen by the oscillator to be reduced above the time constant,

$$f_{3dB} = \frac{1}{2\pi RC} \tag{2}$$

For R=500 and C=500pF this occurs at 6.37MHz. Therefore placing the 500pF capacitor across the oscillator output should reduce the high-frequency spectrum of the signal.

3. Long leads of components introduce an inductance that is in series with the element, Llead [ll For a capacitor this causes a resonance at

$$f = \frac{1}{2\pi\sqrt{L_{lead}C}} \tag{3}$$

above which the capacitor with long leads behaves as an inductor. For lead lengths of ½ inch the inductance is approximately L_{lead} = 14nH [1]. This gives a resonant frequency of 60 MHz. Consequently, above this frequency, the capacitor behaves as an inductor and does not "short out" the 50Ω impedance. This effect and the resonance frequency of around 60MHz should be evident in the above spectrum analyzer plots.

5. References

1. C.R. Paul, Introduction to Electromagnetic Compatibility, John Wiley & Sons, NY, 1992.
2. H.W. Ott, Noise Reduction Techniques in Electronic Systems, John Wiley & Sons, NY, 2nd Edition, 1988.

Common-Mode Currents and Radiated Emissions of Cables

Clayton R. Paul
University of Kentucky, Dept. of Electrical Engineering

1. Objective

To illustrate the importance of common-mode currents in the radiated emissions of interconnect cables. To illustrate the use of current probes in measuring these common-mode currents and to show that accurate predictions of the emissions can be obtained with these measured currents.

2. EQUIPMENT

- The oscillator and board prepared in the experiment **Effect of Pulse Rise/Fall Time on Signal Spectra**.
- A 1½ foot (18 inches or 45.72 cm) length of 300Ω, parallel wire "twin lead".
- One 300Ω, 1/8W carbon resistor.
- One BNC female panel mount connector.
- One 7805 DC regulator and a 9V battery.
- One current probe suitable for the frequency range of 10 MHz to 100 MHz.
    - Preferably this should have its associated calibration chart of transfer impedance. A suggested type is the F-33 probe available from Fischer Custom Communications, Inc. The probe transfer impedance, $Z_T = 20\log_{10}(V/I)$ is typically 15dBΩ from 10 MHz to 100 MHz [1]. If such a probe is not available, one can be constructed using a ferrite core (doughnut shape) suitable for the frequency range. Wind numerous turns of magnet wire around it. The magnetic flux due to the co=on-mode current passing through the doughnut concentrates in the core and induces, by Faraday's law, a voltage at the terminals of the windings [1]. Such a homemade probe will need to be calibrated. This can be done by passing a known current level through the core and measuring the induced voltage in the windings. This gives, at each frequency, the probe transfer impedance, $Z_T = \frac{V_{windings}}{I_{core}}$ [1]. If the signal $V_{windings}$ is too small for the spectrum analyzer, it may be necessary to use a wideband preamp. The core should also have a small air gap at some point on its periphery so that when placed around the current to be measured it will not "load down" the circuit.
- A spectrum analyzer (50Ω) suitable for sweeping the frequency range 1 MHz to 100 MHz.
- A wideband preamp such as the HP8447D 25dB preamp.
- A 60 inch (1.52m) length of 300Ω twin lead. This will be used to construct a folded dipole antenna typically used for standard TV reception which is half-wave resonant at the 25th harmonic of the oscillator, 100MHz [2, 3]. The antenna factor of a half-wave folded dipole can be computed and gives [1, 2, 3]

$$E_{ant}(dB\mu V/m) = 20\log_{10} f(MHz) - 2.15 + V_{ant}(dB\mu V) - 37.6 \qquad (1)$$

- A 300n-75n standard TV BALUN which can be purchased at any electronics shop.
- One BNC male/male connector.

3. Procedure

3.1 Device Construction

1. Solder the 300n resistor to one end of the twin lead and the BNC panel mount connector to the other end.
2. Construct the oscillator board described in the experiment **Effect of Pulse Rise/Fall Time on Signal Spectra** and attach to the twin lead with the BNC male/male connector.
3. Construct a compact, regulated 5V DC power supply with the 9V battery and the 7805 regulator chip. Connect to the oscillator board with short leads.
4. Construct the folded dipole by shorting the two ends of the length of twin lead. At the midpoint insert the 300n side of the BALUN in series with one side of the dipole.

3.2 Measurement of Radiated Emissions

1. Place the twin lead parallel to and a height of 1m above the ground outside of the building. Place the measurement antenna 3m away from the twin lead (the FCC Class B measurement distance), 1m above the ground and parallel to the twin lead.
2. Connect the antenna to the spectrum analyzer through the 25 dB preamp and record the antenna voltage (turn on the oscillator first) at 100 MHz (the 25th harmonic of the 4 MHz oscillator) as well as at a number of the lower harmonics of the oscillator.
3. Using the antenna factor calibration for the folded dipole given above convert the measured voltages to electric field values and plot them versus the FCC Class B limit [1].

The author measured voltage at 100MHz was 55dBμV. Subtracting the 25dB gain of the preamp and substituting into (1) gives E=30.25dBμV/m.

3.3 Measurement of Common-Mode Current on the Cable

1. Place the current probe around the twin lead midway along its length.
2. Connect the current probe to the spectrum analyzer through the 25dB preamp with a length of 5.00 coaxial cable and record the measured levels at the harmonics of the oscillator.
3. Using the current probe's transfer impedance calibration chart convert the measured voltages to the (common-mode) current on the cable at each harmonic. The author measured a value of 57dBμV at 100 MHz. Subtracting 25dB for the preamp gives 32dBμV. This is converted to the current by subtracting the current probe transfer impedance (15dBΩ for the F-33 probe) to give a common-mode current at the 25th harmonic of 100MHz of 17dBμA.

3.4 Prediction of the Emissions

1. Using the measured common-mode current levels try to predict the measured electric field emissions using [1]

$$E = 1.257\,x10^{-6}\,\frac{I_C\,f\;\mathrm{L} = 45.72cm}{d = 3m} \qquad (2)$$

For the experiment, the author obtained a measured value of 30.25dBμV/m at 100 MHz and a predicted value using the measured common-mode current of 36.6dBμV/m using (2).

2. Plot the predictions vs. the measured emissions in dBμV/m on semilog graph paper (1 cycle).

4. Theory

4.1 Common-Mode Currents and their Significance

Consider Figure 1 in which we have shown two parallel wires of length L and separation *d.* The currents in the two wires at a crossection are denoted I_1 and I_2. These may be decomposed into *differentia1-mode* components, I_D, and *common-mode* components, I_C, as

$$I_1 = IC + ID \tag{3a}$$

$$I_2 = IC - ID \tag{3b}$$

Adding and subtracting these give

$$I_C = \frac{I_1 + I_2}{2} \tag{4a}$$

$$I_C = \frac{I_1 - I_2}{2} \tag{4b}$$

The *differentia1-mode* currents are the functional or desired currents that are predicted by Kirchhoff's laws and the usual lumped-circuit theory. These are equal in magnitude but oppositely directed at a cross section. The *common-mode* currents are equal in magnitude but directed in the same direction at a cross section. They are usually much smaller than the differential-mode currents and are not necessary for function performance. These are not ideally present and are due to asymmetries, nearby metallic planes, etc. However, Figure 1 shows that the electric fields due to the differential-mode currents are oppositely directed as are the differential-mode currents. These fields therefore subtract but because the currents are not collocated, these fields do not cancel. However, the common-mode currents and their associated fields are directed in the same direction and so add. Consequently, a "small" amount of common-mode current can result in the same radiated electric field as a much larger differential-mode current. It is for this reason that common-mode currents tend to be the dominant contributors to the radiated emissions of parallel conductors such as cables. A common method of suppressing these common-mode currents is with ferrite common-mode chokes [1]. The rudimentary current probe suggested above will act, to some degree, as a common-mode choke and will affect the common-mode current. Practical current probes have a small air gap to minimize this loading.

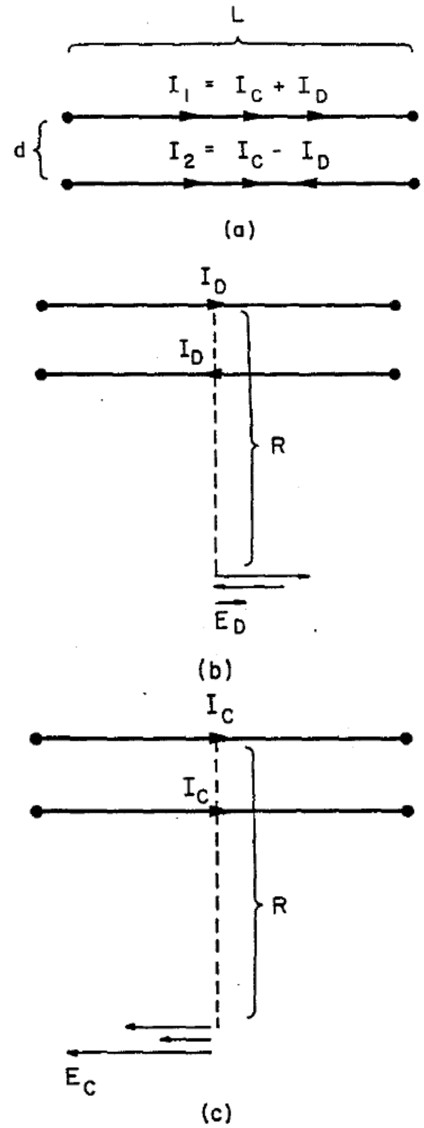


Fig. 1. Illustration of the effect of common-mode and differential-mode currents on the radiated emissions of cables.

5. References

1. C.R. Paul, Introduction to Electromagnetic Compatibility, John Wiley & Sons, NY, 1992, Chapter 8.

2. R.K. Keenan, Digital Design for Interference Specifications, The Keenan Corporation, Pinellas Park, FL, 1983.

3. W.L. Stutzman and G.A. Thiele, Antenna Theory and Design, John Wiley, NY, 1981.

Format of Experiment/Demonstration Submissions

We encourage you to submit any experiments/demonstrations that involve EMC principles for inclusion in future editions of this booklet. If you wish to submit, please follow this suggested format in preparing that submission:

Title
Author
Affiliation

1. Objective
Concise but complete statement of what the person doing the experiment is expected to get out of it.

2. Equipment
List all essential equipment and any necessary minimum requirements of that equipment, such as bandwidth, sensitivity, etc. Since the intent of this booklet is widespread use, don't list equipment that can be found only in certain specialized labs. Try to use oscilloscopes whose bandwidths are not greater than 50 MHz. Sinusoidal oscillators with frequency capabilities no higher than 10 to 50 MHz should be used. Pulse or function generators should not require pulse repetition rates greater than 1 MHz, nor pulse rise/fall times less than 10 to 50 ns.

Specialized test jigs should not be required; use of a soldering iron, readily available wire, nuts and bolts, and pieces of wood or metal are examples of types of items that should be used to construct the experiment. Don't require the use of a spectrum analyzer, unless absolutely necessary, since these are not as commonly available as oscilloscopes. Be clever; try to demonstrate the principle without the need for elaborate or sophisticated test equipment or jigs. For example, an FM radio receiver might be usable in place of a $40,000 EMI receiver to demonstrate a principle. Remember, the goal is to demonstrate a principle, not necessarily to make accurate measurements.

3. Procedure
Give step-by-step explicit instructions of how you want the experiment performed and in what order. Don't leave anything to the imagination. Don't assume an experienced test engineer will be performing the experiment. Include as many diagrams and pictures as possible to guide the instructor.

Once you have compiled your submission in this format, run the experiment per your written procedure to uncover any "bugs", not just in the experiment but also in your instructions. This is a good time to take additional pictures to include for guidance. It is preferable to have someone not as experienced as you run the experiment.

4. Theory
In this section give a simple but sound explanation of what is going on in the experiment in terms of the basic principles you are trying to demonstrate. Use only the minimum theoretical explanation required to explain it. Don't scare the reader with theoretical details; on the other

hand don't give simplistic "hand-waving" arguments either. It requires a clever person who truly understands the basic principles to "walk this thin line".

You may wish to give examples of specific instances where these principles have application. Don't use "buzz words" such as: "The rum-flam principle demonstrated above can be used in the ABM system to drive the FRK in the DUT". Imagine yourself trying to explain the relevance of these principles to a new graduate on his/her first day on the job.

5. References

Give only those references directly germane to elaborating on a specific point. These should be items in which the reader can find additional details concerning the principle. These should also be items which are clearly written and available to the reader. Textbooks are usually preferable to journal or symposium articles since they usually contain more detail and are usually more available and more suitable to teaching than a journal or symposium article.