Experimental Demonstration of EMC Principles

Thanks for your participation in this electromagnetic compatibility (EMC) seminar. Most engineers and technicians using or designing electronic systems have not had any formal education concerning EMC principles and design techniques. Learning how to solve EMC problems on the job can be very expensive for the employer and frustrating for the engineer. Most of the electromagnetic and circuit principles involved are very simple. However, the complexity of many systems masks the logic and simplicity of possible solutions.

The objectives of this EMC seminar are:

1. To review basic EMC principles;
2. To experimentally demonstrate these principles; and,
3. To show some practical examples of how these principles are used to reduce EMI.

The workbook greatly reduces the amount of note taking required, but still requires your active participation to record key information and to complete the example problems.

A complete 2-day version of this course is available for in-house training. The topics can be modified to fit your special interests. A 15-hour videotaped version of the complete course is also available. See pages near the end of these notes for more details.

Please contact me if you have any questions about this course or you need assistance with an electrical noise problem.

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COURSE INSTRUCTOR

Dr. Tom Van Doren is a professor of electrical and computer engineering at the University of Missouri-Rolla. Dr. Van Doren has 32 years of teaching and industrial experience in the areas of electromagnetic compatibility, data acquisition, microwave communication systems, and semiconductor device fabrication. Over the past 21 years, more than 18,000 engineers and technicians have attended his short courses on "Grounding and Shielding of Electronic Systems" and "Circuit Board Layout to Reduce Electromagnetic Emission and Susceptibility."

IN-HOUSE TRAINING

A two-day version of this program, with the topics tailored to your special interests, is available for in-house training. A typical program consists of 14 hours of lectures, demonstrations, and practical problem solving. The total cost for a customized two-day in-house program for a maximum of 35 people, including all travel expenses and 35 copies of the workbook, is $12,800. Please contact Tom at vandoren@umr.edu or 573-341-4097 for additional details or to schedule an in-house presentation.

REFERENCES

Electromagnetic Compatibility and Signal Integrity:
1. "Introduction to Electromagnetic Compatibility," Clayton R. Paul, 1992,
   ISBN 0-471-54927-4, John Wiley.
2. "High-Speed Digital Design," Howard W. Johnson & Martin Graham, 1993,
   ISBN 0-13-395724-1, PTR Prentice Hall.
3. "Noise Reduction Techniques in Electronic Systems," Henry Ott, 2nd Edition, 1988,
   ISBN 0-471-85068-3, John Wiley.
4. "Controlling Radiated Emissions by Design," Michel Mardiguian, 1992,
   ISBN 0-442-00949-6, Van Nostrand Reinhold.
5. "High-Speed Digital System Design," Stephen Hall, Garrett Hall, James McCall, 2000
   ISBN 0-471-36090-2, Wiley Interscience.

Electrical Safety:
1. "Soares Book on Grounding," 2002, B6-RES8802, NFPA International (www.nfpacatalog.org).
2. "User's Guide to the National Electrical Code," 2002, B6-GDNEC02, NFPA International (www.nfpacatalog.org).

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DISCLAIMER

Information furnished herein is believed to be accurate and reliable, however, no responsibility is assumed for any errors. The user assumes full responsibility for the accuracy and appropriateness of this information.

The recommendations and techniques presented in this course have been used to solve many electrical noise problems. Electromagnetic compatibility is a very controversial subject with many conflicting opinions concerning the best techniques to use to improve EMC. Each person must determine whether the techniques described herein are suitable and safe for any specific applications. At no time should safety be sacrificed to reduce electrical noise.

Experimental Demonstration of EMC Principles

presented by

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1. What path does current take?
2. Resonance
3. E & H Field Containment by Self Shielding
4. Reasons for Grounding
5. Coupling Mechanisms & Equiv. Circuits
6. Externally Added E-Field Shielding
7. Externally Added H-Field Shielding
8. Externally Added EM Wave Shielding

1-1

1. What Path Does Current Take?

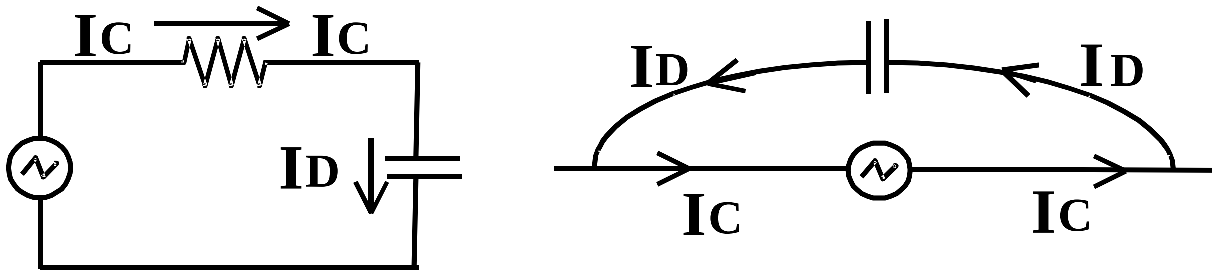
Misconceptions **that can cause EMI:**

Currents go to ground. (WRONG)
Currents take the path of least resistance. (WRONG)
Ground is the signal current return path. (WRONG)
A single straight wire has self inductance. (WRONG)

1-2

CONDUCTION CURRENT (I_C) – “FREE” CHARGES

DISPLACEMENT CURRENT (I_D) –“BOUND” CHARGES



Conduction currents consist of unbound (free) charged particles, such as electrons, moving through a conductor, such as a metal wire. Displacement currents consist of bound charges, such as ions, oscillating a short distance about a fixed location. The current through a capacitor is a displacement current. The current through air is also a displacement current.

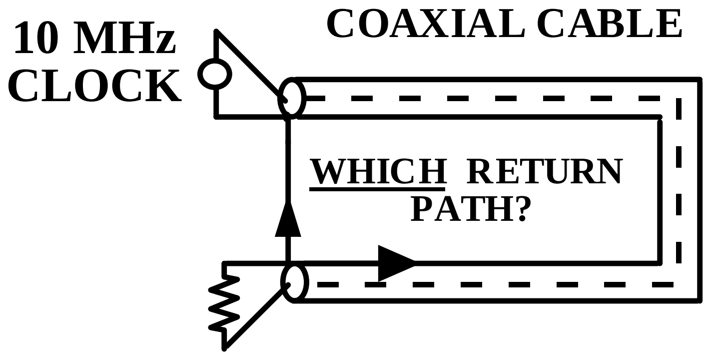
#1. EACH CURRENT RETURNS TO ITS SOURCE. 1-3
#2. CURRENT TAKES THE PATH OF LEAST IMPEDANCE, FOR STEADY-STATE CONDITIONS.

Currents do not usually go to ground, but every current eventually returns to its' source. Sinusoidal steady-state current takes the path of least impedance, not least resistance. The concept of least impedance is discussed in detail in this chapter.

A current path consists of a minimum of two parts, the part where the current goes out toward the load and the part where the current returns from the load. The current goes out and back simultaneously. The outgoing and returning portions of the current travel together down the transmission line.

1-4

WHAT PATH DOES CURRENT TAKE?



What path does current take? This is a crucial, basic question. It is often necessary to know the location of the output and return paths for every current in a system to within ± 1 mm.

Often the outgoing current path is well known, but the return path is uncertain. Both the outgoing and return paths must be known. A failure to recognize the importance of the current return path is one of the major causes of electrical interference problems. An improperly located return path increases both susceptibility and emission.

For the coaxial cable shown, the MHz currents all return on the inside surface of the outer conductor of the coaxial cable.

1-5

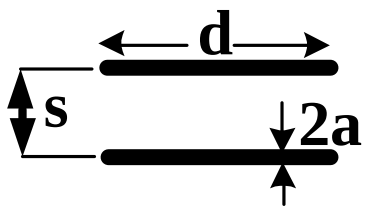
EQUIVALENT CIRCUIT FOR SIGNAL WIRING

= R, L, C ??

DEFINITION + SPECIFIC GEOMETRY = UNIQUE FORMULA

A current path typically consists of resistance R, self inductance L, and self capacitance C. The definition for any one of these parameters applied to specific conductor geometry yields a unique formula for that parameter for that specific geometry. This formula cannot be for other conductor geometries.

SELF CAPACITANCE 1-6

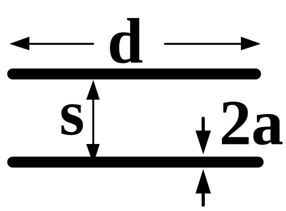
Definition	Specific Geometry	Unique Formula
$C \equiv \frac{\lvert Q \rvert}{\lvert V \rvert}$	Two wires of radius “a” 	$C = \frac{\pi \varepsilon d}{\cosh^{-1}(s/2a)}$

2 CONDUCTING SURFACES ⇒ 1 CAPACITOR

Self capacitance is defined as the ratio of charge to voltage difference magnitudes. When this definition is applied to a specific geometry, such as two parallel wires, the capacitance formula usually involves conductor surface area and conductor spacing.

Two metal surfaces are required to produce one capacitor.

SELF INDUCTANCE 1-7

Definition	Specific Geometry	Unique Formula
$L \equiv \frac{\Psi}{I}$		$L \equiv \frac{\mu d}{\pi} \cosh^{-1}(s/2a)$

ONE COMPLETE LOOP ⇒ ONE INDUCTANCE

Self inductance L is defined to be the amount of magnetic flux Ψ linking (encircling) a current I divided by the current producing the flux, $L \equiv N\Psi/I$. Even though the self inductance is defined in terms of magnetic flux and current, the actual self inductance is determined by the magnetic permeability μ of the medium and the size, length and spacing of the conductors that form the current path. The self-inductance increases if the current loop area increases and the self inductance decreases as the wire size (surface area) increases.

Self-inductance is a property of a closed loop. The inductance cannot be determined until the entire loop, output path and return path, has been specified.

$$L = \frac{\mu d}{\pi}\cosh^{-1}(s/2a) \approx \frac{\mu d}{\pi}\ln(s/a) \qquad \text{1-8}$$

MINIMIZE WIRE LENGTH AND SPACING.

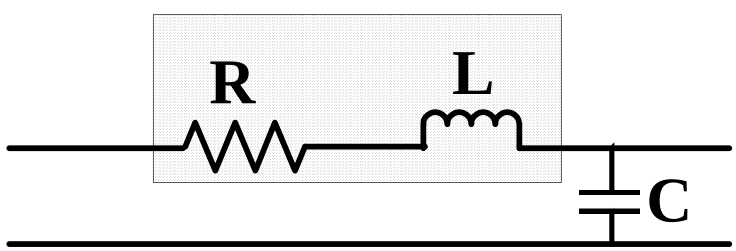
MAXIMIZE WIRE SIZE.

A SINGLE, STRAIGHT CONDUCTOR DOES NOT POSSESS SELF INDUCTANCE BECAUSE THERE IS NO COMPLETE CURRENT LOOP!

The formula for the self inductance per unit length of two parallel, infinitely long wires is shown above. If the wire spacing "s" is much greater than the wire radius "a", then the $\cosh^{-1}$ can be approximated by the ln function.

Self inductance is a property of a complete current path (loop). A single, straight wire is not a complete path and this structure does not possess the property of self inductance.

WIRING EQUIVALENT CIRCUIT 1-9



$2\pi fL > R$

FOR FREQUENCIES > 3 kHz

Wiring, whose length < λ/20, can be considered as a lumped rather than distributed circuit. Ignoring temporarily the shunt capacitance, consider only the impedance of the wire series resistance and series self inductance. It will be demonstrated later that for frequencies > 3 kHz the inductive reactance is greater than the resistance. This is true even when the resistance increase due to the skin effect is included. The conclusion that $2\pi fL > R$ for f > 3 kHz is **only true** for **wiring** and is not true for individual components, such as relay coils or resistors. This is true for any type of wiring: twisted pair, coaxial cable, ribbon cable, circuit board traces, etc.

1-10

LEAST IMPEDANCE MEANS

FOR f < 1 kHz	FOR f > 10 kHz
LEAST RESISTANCE	LEAST REACTANCE LEAST INDUCTANCE
ALL POSSIBLE PATHS	SMALLEST CURRENT LOOP AREA

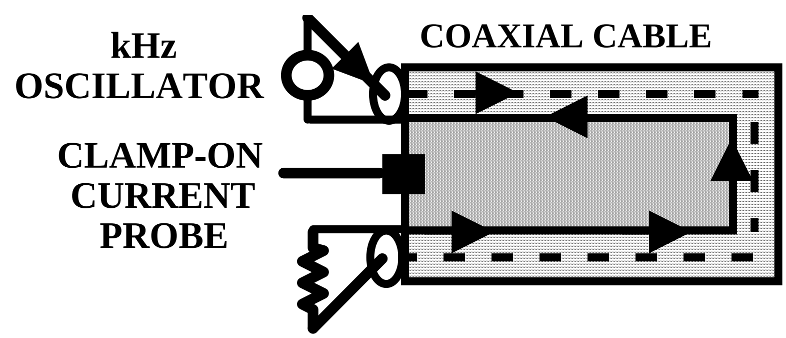
The concept of least impedance can be simplified to either least resistance or least self inductance depending on the frequency. For frequencies < 1 kHz current takes the path of least resistance. This means that the current will take all possible paths depending on their resistances. For frequencies > 10 kHz current takes the path of least reactance, which usually means least self inductance. The path of least inductance is often the one with the smallest loop area.

1-11

DEMONSTRATION – CURRENT TAKES THE PATH OF LEAST IMPEDANCE

f = 1 kHz, ALL PATHS.

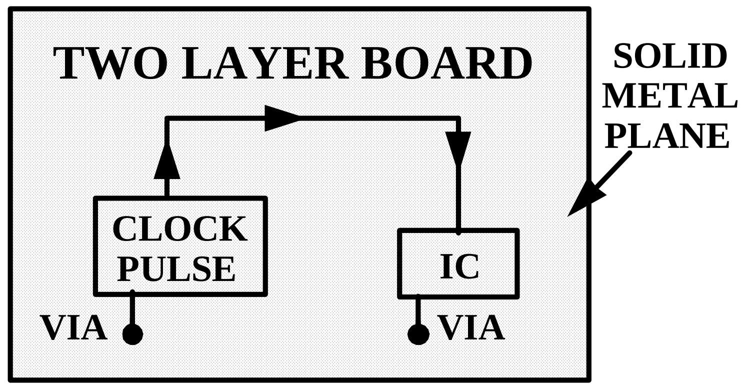
f = 10 kHz, SMALLEST CURRENT LOOP AREA.



The clamp-on current probe measures the current in the short 2" connection between the two coax connectors. At oscillator frequencies of a few hundred Hz, current takes the path of least resistance – which means all possible paths. There are two return paths. Most of the current takes the shortest connection because this is the least resistance. The current through the clamp-on probe nearly equals the total current through the load resistor. At 1 kHz there is a slight decrease in the current through the clamp-on probe. At 10 kHz there is a significant decrease in the current. This demonstration shows that somewhere between 1 kHz and 10 kHz the inductive reactance becomes larger than the resistance of the current path. The total current path, output and return, must be considered to determine loop area or inductance.

WHERE IS THE CURRENT RETURN PATH LOCATED?

1-12

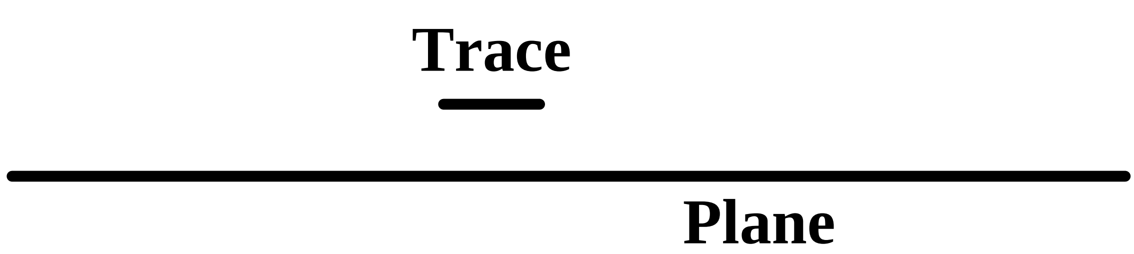


The circuit board consists of two layers: individual traces on the top layer, and a solid plane on the bottom layer. **Precisely** where is the clock return current **located** in the solid metal plane? The DC component spreads throughout the entire plane, with much of the **DC** current taking the **shortest** path between the two vias. However, the fundamental frequency and harmonic components take the path of least impedance, which is the least inductance or smallest loop area. These currents return directly beneath the outgoing current trace. This minimizes the loop area of the total current path.

This concept also applies to multilayer circuit boards. For example, on a 12 layer board a specific current typically uses only 2 or 3 of the 12 layers. For that specific current, the 12 layer board acts essentially as a 2 or 3 layer board.

1-13

CURRENT DISTRIBUTION AND MAGNETIC FLUX DISTRIBUTION FOR A MICROSTRIP LINE (CROSS-SECTIONAL VIEW)



Assume that a current in the MHz frequency range is traveling down the Trace and returning in the Plane. 80% of the return current in the Plane will be located in a width equal to six times the height of the Trace above the Plane and centered on the Trace. The remaining 20% of the return current will spread across the top and bottom sides of the Plane. There will be an additional concentration of the current along the two edges of the Plane. Most of the magnetic flux will encircle the Trace.

1-14

FOR WIRING:

$$\text{PHASE VELOCITY} = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{\mu\varepsilon}}$$

μ = MAGNETIC PERMEABILITY

ε = DIELECTRIC PERMITTIVITY

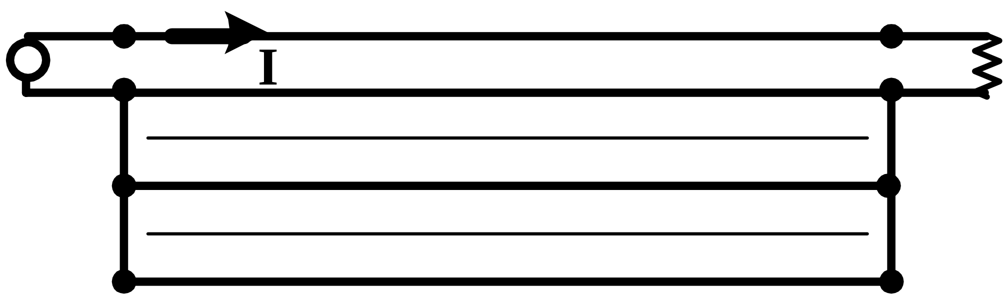
$LC = \mu\varepsilon$ = USUALLY A CONSTANT

The phase velocity of a sine wave along a transmission line is determined by the per-unit length inductance and capacitance, $v = 1/\sqrt{LC}$, and by the permeability μ and permittivity ε of the medium surrounding the wires, $v = 1/\sqrt{\mu\varepsilon}$. Hence, $LC = \mu\varepsilon$. Usually μ and ε are constants, so LC = constant. This is a very useful relationship.

Whatever is done to increase C will automatically reduce L and vice versa. We can use our knowledge of capacitance to predict how changes in the size and spacing of conductors will affect the inductance. $LC = \mu\varepsilon$ is only valid for wiring and does not apply to lumped or discrete inductors and capacitors.

1-15

WHERE IS THE CURRENT RETURN PATH FOR f = 1 kHz AND f = 1 MHz IN THIS RIBBON CABLE?

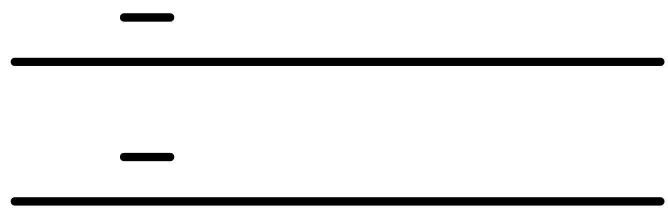


At 1 kHz the current divides equally between the 3 return conductors because they each have the same resistance. At 1 MHz the 3 loop self inductances combined with the 3 mutual inductances cause most of the current to take the smallest loop area path.

WHAT IS THE EFFECTIVE LOOP SIZE FOR MICROSTRIP: 1-16

At f = 1 MHz?

At f = 1 kHz?



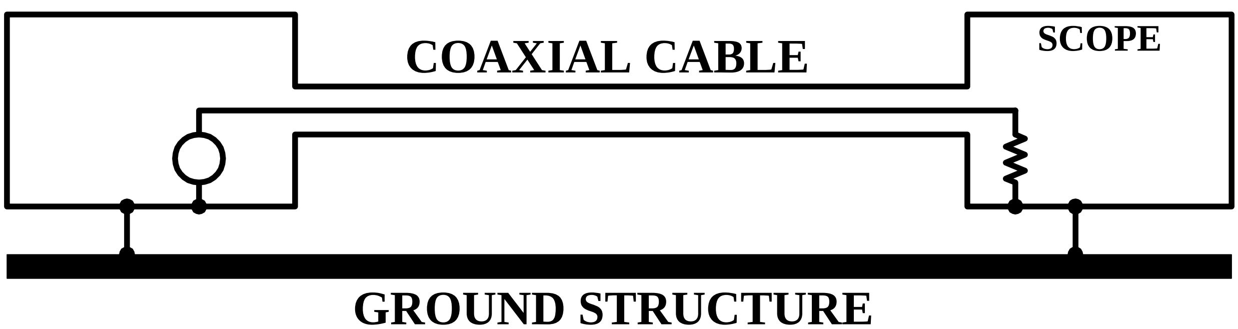
CONCLUSION: kHZ CURRENTS SHOULD NOT BE ROUTED THROUGH PLANES.

At 1 MHz most of the return current is centered beneath the trace and the effective loop are is the trace length times the trace–to– plane spacing.

At 1 kHz, the return current spreads uniformly across the plane. The geometric centroid of the return current path is the center of the plane. The effective loop area in this case is much larger than for the 1MHz case.

1-17

WHAT IS THE SIGNAL CURRENT PATH FOR f = 1 kHz AND f = 1 MHz?

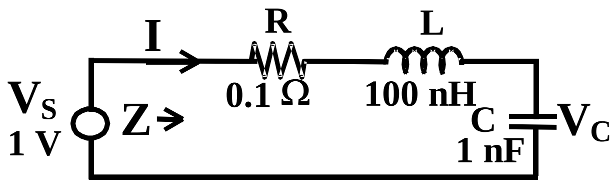


Current At 1 kHz will take all possible paths. Some of this current returns on the outer conductor of the coaxial cable and some returns through the ground structure.

The 1 MHz current returns on the inside surface of the coaxial cable outer conductor.

2. RESONANCE

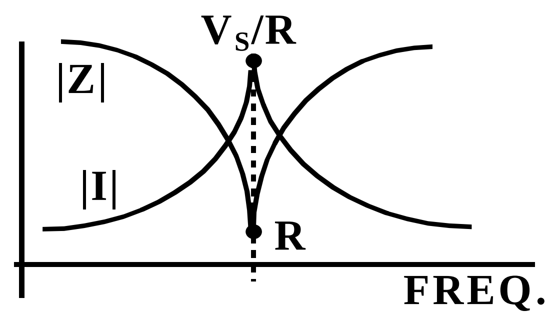
2-1



AT RESONANCE:

$$I = V_S/R = 10\ A$$

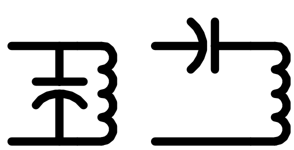
$$|V_C| = \left(\frac{2\pi}{R}\sqrt{\frac{L}{C}}\right)|V_S| = 628V$$



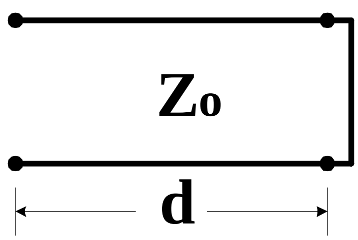
EMI problems are more likely to occur near frequencies where circuits, cables, or enclosures are resonant. Unusually large values of current (magnetic fields) or voltage (electric fields) can occur near resonant frequencies. The large field strengths produced at resonance, combined with poor field containment, can produce serious EMI problems.

The circuit shown is driven by a 1 V source. At resonance the current is 10 A and the voltage across the capacitor is 100 V.

L & C VALUES DETERMINE $f_R = 1/(2\pi\sqrt{LC})$ FOR A LUMPED CIRCUIT.



DIMENSIONS DETERMINE f_R FOR DISTRIBUTED CIRCUIT. 2-2



$$d = n\lambda/4$$

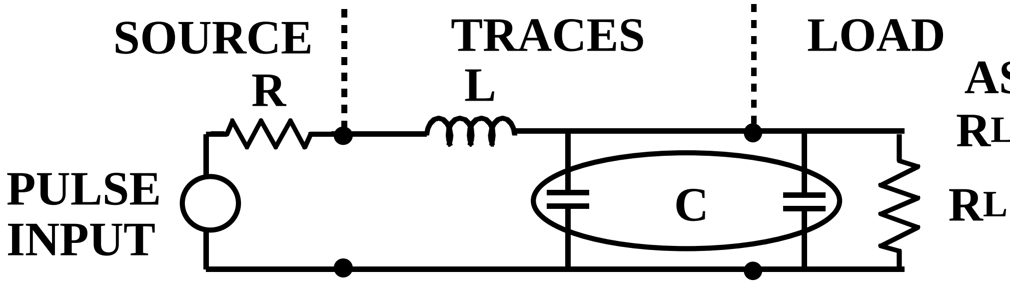
$$f_R = nv/4d,\ n=1,2,3\ldots$$

v = velocity in medium.

Both lumped and distributed circuits can resonant. For lumped circuits the resonance frequencies are determined by the values of the lumped inductances and capacitances. For distributed circuits, the resonance frequencies are determined by the physical dimensions of the metallic structure that is resonating. A given structure usually has many resonance frequencies. The lowest resonance frequency is determined by the largest dimension of the metallic structure.

2-3

CONDITIONS FOR RINGING OR ROUNDING



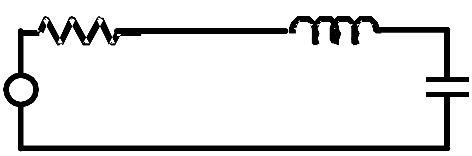
ASSUME
$R_L >> 1/\omega C$

RINGING → UNDER DAMPED → $L > R^2C/4$

Many pulse circuits can be represented by the lumped equivalent circuit shown. The source has a series resistance, the interconnecting circuit board traces have series inductance and shunt capacitance, and a typical logic load has a parallel resistance and capacitance. Assume that the capacitive reactance of the cable plus load ($1/\omega C$) is much less than the load resistance (R_L) at high frequency. Then R_L can be neglected and the condition for ringing (under damped) is $L > R^2C/4$. The condition for rounding (over damped) is $L < R^2C/4$.

AN EXAMPLE CALCULATION OF THE MAXIMUM INDUCTANCE PERMITTED TO AVOID RINGING

2-4



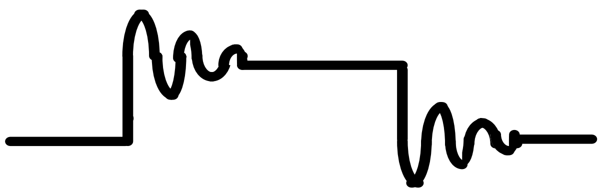
R = 10 Ω
GATE OUTPUT RESISTANCE
C = 20 pF,
LINE + LOAD CAPACITANCE

$L > R^2C/4 = 0.5$ nH CAUSES RINGING.
(KEEPING L < 0.5 nH IS IMPOSSIBLE!)

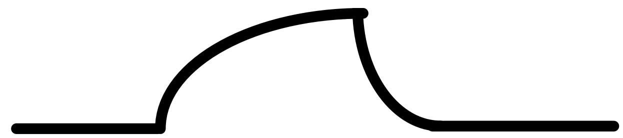
The inductance needed to cause a circuit to ring is often surprisingly small. For the example shown, an inductance greater than 0.5 nH causes ringing. A 2 cm long trace directly above a return plane could easily exceed this inductance limit.

2-5

RINGING INDICATES EXCESSIVE WIRING INDUCTANCE



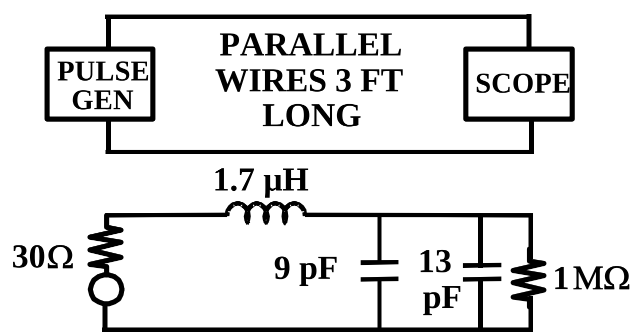
ROUNDING INDICATES EXCESSIVE CAPACITANCE



The shape of the rising and falling edges of high-speed pulse signals can indicate the cause of the signal distortion. Ringing usually indicates excessive wiring inductance. Ringing is an exponentially damped sinusoidal oscillation. Both inductance and capacitance are required to have ringing. The capacitance is typically a necessary part of the load being driven. Unnecessary wiring loop area is usually the cause of the excessive inductance.

Excessive rounding of the edges indicates a circuit dominated by series resistance and capacitance. The resistance may be a necessary part of the driver circuit. This leaves the wiring capacitance as the only adjustable value, assuming that the load capacitance is fixed. Remember that decreasing the wiring capacitance will increase the wiring inductance and may cause a rounded waveform to become a ringing waveform.

2-6



$$L > R^2C/4 \Rightarrow \text{RINGING}$$

$$f_{OSC} \approx 25\ \text{MHz}$$

For oscillations to occur the circuit must be under damped and there must be energy available at the oscillating frequency. A RLC series circuit is under damped whenever $L > R^2C/4$. In this case $L = 1.7\ \mu H > R^2C/4 = .0047\ \mu H$, so the circuit is under damped. If the pulse generator output contains some energy at the circuit resonance frequency, then the current and voltage waveforms will oscillate.

3-1

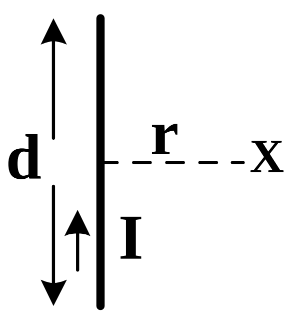
3. Electric and Magnetic Field Containment by Self Shielding

Self shielding—the metal is part of the intentional signal current path!

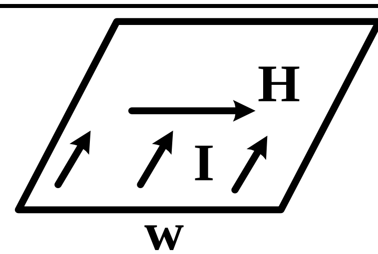
Self shielding is more effective then externally added shielding techniques because self shielding adds negligible weight or cost, covers a very broad frequency range and can contain electric fields, magnetic fields and electromagnetic waves all at the same time.

3-2

CURRENTS GENERATE MAGNETIC FIELDS. MAGNETIC FLUX ENCIRCLES THE CURRENT.



$H = I/(2\pi r)$, if $d >> r$.

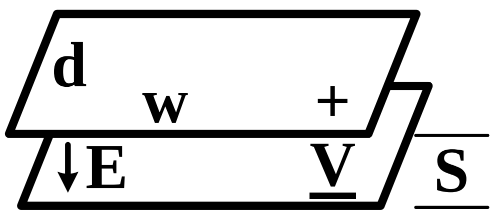


H = I/w near a flat conducting surface

Current (moving charges) generates a magnetic field. The magnetic flux encircles the current path. The spatial variation of the magnetic field intensity H depends on the current distribution in the transverse plane. A current filament produces a magnetic field that varies inversely with the radial distance from the filament.

VOLTAGE DIFFERENCES GENERATE ELECTRIC FIELDS. ELECTRIC FLUX PASSES FROM + TO – CHARGE. 3-3

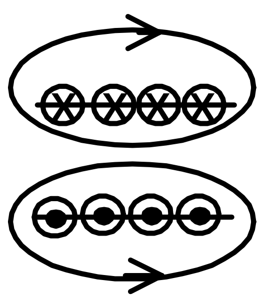
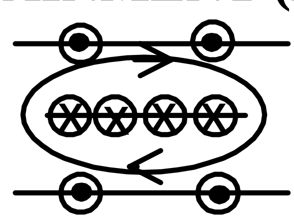
$V \rightarrow Q \rightarrow E$



$E = V/s$,
If d & w >> s

Voltage differences create unneutralized charges. The charges create electric fields. Hence, voltage differences create electric fields. The electric field (flux) begins on the positive charge and ends on the negative charge. Consider the two oppositely charged parallel plates shown above. If d & w >> s, then E = V/s. The electric field is constant everywhere between the two plates.

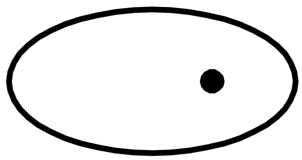
E & H CONTAINMENT REDUCES CAPACITIVE & INDUCTIVE COUPLING 3-4

SMALL L, BUT POOR CONTAINMENT.	SMALL L & EXCELLENT CONTAINMENT (M = 0).
	

To control magnetic field noise coupling, it is desirable to: 1) reduce the total amount of magnetic flux generated; and 2) contain the magnetic flux within a restricted area. Reducing the self-inductance L reduces the amount of magnetic flux generated. To contain the magnetic flux, the return current must be allowed to surround the outgoing current.

REQUIREMENTS FOR E & H FIELD COMTAINMENT 3-5

COAXIAL CONFIGURATION



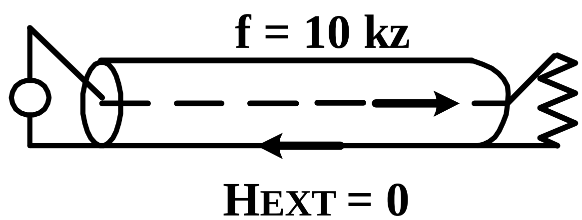
1. **EQUAL & OPPOSITE CURRENT.**
2. **ONE PATH <u>SURROUNDS</u> THE OTHER.**
3. **f > 100 kHz**

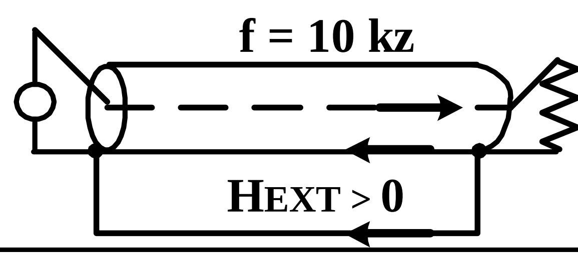
   OR

CIRCULAR & CONCENTRIC OUTER PATH.

Electric and magnetic field containment requires that the return current path <u>completely</u> <u>surrounds</u> the outgoing path. For frequencies below approximately 100 kHz, the return path must be circular and concentric with the outgoing path. For frequencies > 100 kHz the return path does not have to be circular or concentric.

3-6 DEMO – H FIELD FROM COAXIAL CABLE





CONCLUSION: FIELD CONTAINMENT REQUIRES THAT THE RETURN CURRENT PATH <u>SURROUNDS</u> THE OUTGOING CURRENT PATH.

When all of the signal current returns on a path that surrounds the outgoing path, then the E and H fields are contained. For coaxial cable grounded at both ends, another return path exists outside the cable. At frequencies below a few kHz, some of the current will take this external path resulting in E and H fields outside the cable.

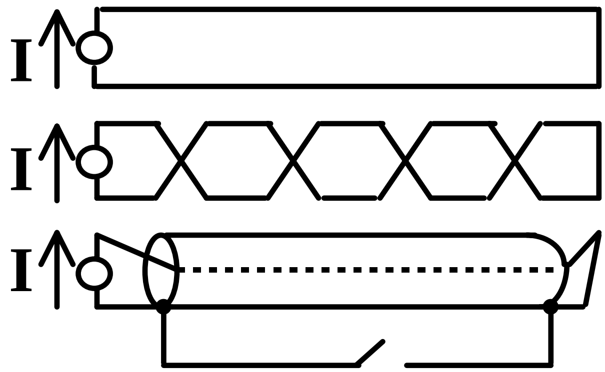
3-7

DEMO: MAGNETIC FIELD EMITTED BY

TWO PARALLEL WIRES:

A TWISTED PAIR:

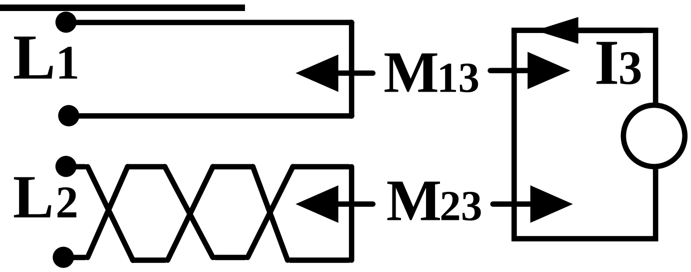
A COAXIAL CABLE:



In this demonstration, the current flowing on the two parallel wires produces an easily measurable external magnetic field. The same current on the twisted pair produces much less magnetic field coupling into the magnetic field sensing probe. This is an example of self shielding. The coaxial cable, without the external loop, produces no externally measurable magnetic field. Below a few kHz the coaxial cable, with the external loop, produces an easily measurable external magnetic field.

3-8

A TWISTED WIRE PAIR REDUCES <u>MUTUAL</u> INDUCTANCE.



$$L_1 \approx L_2 \qquad M_{23} << M_{13}$$

Twisting wire pairs together does not change their self inductance, if the wire-to-wire separation does not change. But, twisting wire pairs can reduce their mutual inductance to other circuits by orders of magnitude. For example, twisting a pair of #22 AWG wires once per inch reduces the mutual inductance by 43 dB compared to untwisted wires. Twisting wires together is an excellent example of self shielding. No material needs to be added to achieve a significant reduction in the mutual inductance. Wrapping the output and return current paths around one another produces the shielding.

3-9

60 Hz MAGNETIC SHIELDING:

#22 AWG WIRE PAIR	Attn (dB)	
UNTWISTED PAIR (REF.)	0	
TWISTED (1 TWIST/INCH)	43	⇐SELF SHIELDING
UNTWISTED PAIR IN ALUMINUM CONDUIT	3	
UNTWISTED PAIR IN STEEL CONDUIT	32	⇐EXTERNALLY ADDED SHIELDING

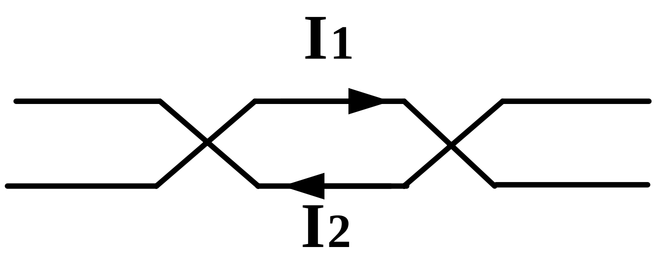
How much twisting is required? This depends slightly on the size or gage of the wire. For #22 AWG, twisting once per inch reduced the magnetically coupled noise by 43 dB, compared to untwisted wire. Two twists per inch only added a few dB of noise reduction.

The important concept to realize is the mutual inductance for a signal loop consisting of two closely spaced wires can be reduced by a factor of 100 (40 dB) if these two wires are simply twisted together at least once per inch. This is self shielding. No added metal is required. The outgoing and return signal current paths must simply be allowed to surround one another.

Placing untwisted signal wires in a thick-walled steel conduit is the "other type of shielding". This can provide some shielding, but the shield is expensive and heavy.

3-10

HOW <u>MUST</u> THE TWO CURRENTS ON A TWISTED PAIR BE RELATED?



CURRENTS MUST BE EQUAL & OPPOSITE!

MANY TWISTED PAIRS DO NOT CARRY EQUAL AND OPPOSITE CURRENTS!

For a twisted pair of wires to provide magnetic-field self shielding, the currents <u>must be equal and opposite</u> on the two wires. That is, the current that goes down one wire must be exactly the same current that returns on the other wire – no more and no less. Twisted pair wire is very often misused by placing unequal and sometimes even unrelated currents on the two wires. It is best to assume that twisted pair wire is being used incorrectly; until it is proven that the currents are equal and opposite.

3-11

REDUCING MAGNETIC COUPLING TO AND FROM A RIBBON CABLE.

1. S 1 S 2 S 3 S 4 S 5 R UNTWISTED WIRES

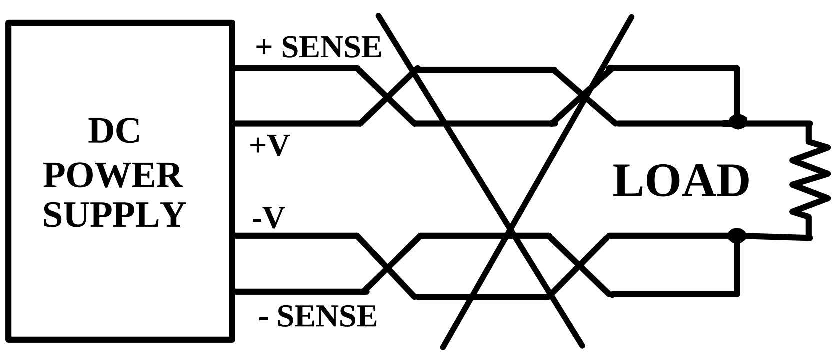
2. (S 1 S 2) (S 3 S 4) (S 5 R) TWISTED PAIRS

3. (S 1 R) (S 2 R) (S 3 R) (S 4 R) (S 5 R) TWISTED

In case 1, all of the signals flow through excessive loop areas which may cause these signals to generate and receive magnetic fields. In case 2, each pair of wires is twisted together. This does not reduce any of the loop areas, because the wires in each pair do not carry equal and opposite currents. The noise cross talk is made worse by this approach. In case 3, a "return" wire is twisted with each signal. Does this approach result in equal and opposite currents on each pair? All of the return wires are connected together on each end of the cable. Signal frequencies below about 1 kHz will return equally divided between all of the return wires. Above 10 kHz most of the signal current will return on the wire in the twisted pair with the outgoing signal.

3-12

MISUSE OF TWISTED PAIR



On long DC power cables, it is sometimes necessary to monitor the DC voltage at the load with a pair of sense leads. This results in a total of four wires, which are convenient to arrange as two twisted pairs. The key question is "which two wires should be twisted together?" The obvious answer is "twist together wires that carry equal and opposite current." In this example, twist the two DC power leads together and twist the two sense leads together. Do not twist leads together that operate at the same voltage, as is shown in the figure. For twisted pair wires to reduce magnetic noise problems, it is essential that the two wires carry only one current. One wire carries the current out to the load and the other wire carries (returns) the current back to the source.

4-1

4. REASONS FOR GROUNDING

To reduce voltage differences that might cause either a

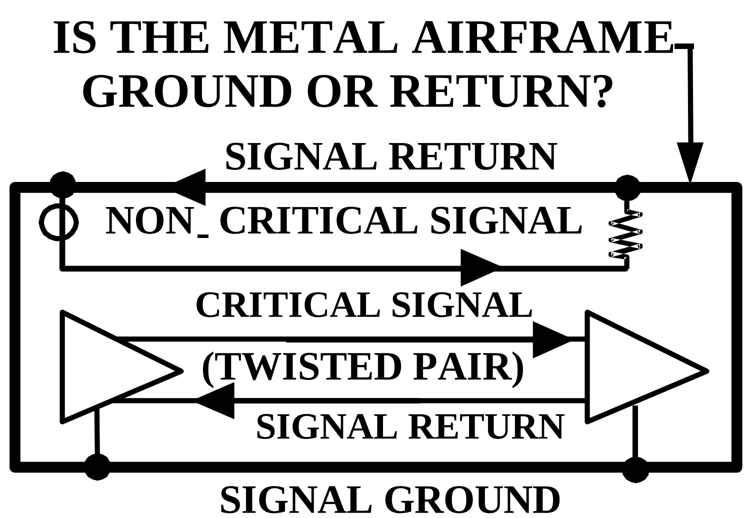
1. SAFETY PROBLEM

or an

2. INTERFERENCE PROBLEM.

Electrical equipment and circuits are grounded to reduce voltage differences that might cause either a safety or an interference problem. Grounding has no relationship to signal routing. Grounding conductors do not carry any significant amount of signal current.

4-2



THE SAME CONDUCTOR CAN BE <u>GROUND</u> FOR ONE SIGNAL AND THE <u>RETURN PATH</u> FOR ANOTHER SIGNAL!

This example shows two signals inside the metal frame of a commercial airliner. One signal is critical to the flight of the airplane and the other signal is not. The non-critical signal uses the metal airframe as the current return path, to save the weight of the return conductor. The metal frame is the return path, and not ground, for the non-critical signal.

The critical signal uses two dedicated conductors in a twisted pair for the output and return paths. For this current, the metal airframe <u>is</u> the ground structure, since none of this signal current flows through the metal frame.

4-3

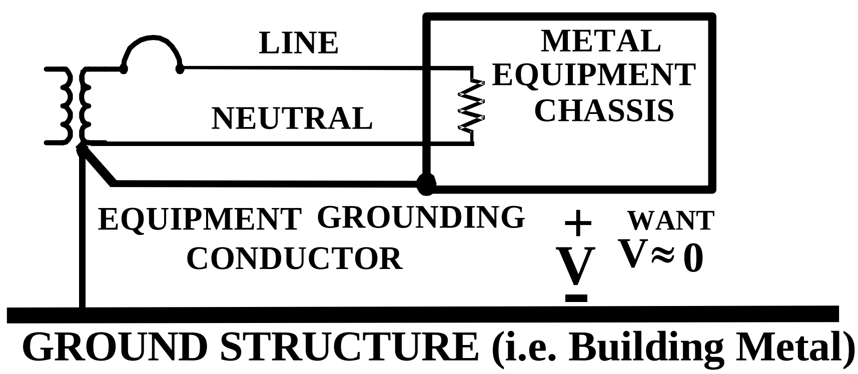
SAFETY GROUNDING – REDUCES VOLTAGE DIFFERENCES BETWEEN EXPOSED CONDUCTING SURFACES THAT MIGHT BECOME ENERGIZED.

SAFETY GROUNDING REQUIRES PROPERLY SIZED AND LOCATED CONDUCTORS TO REDUCE VOLTAGE DIFFERENCES DURING LIGHTNING OR AC POWER FAULTS.

The requirements for safety grounding are listed in Article 250 of the National Electrical Code. The equipment grounding conductor must have sufficient size to carry the fault current until the circuit protective means (circuit breaker) operates. The grounding conductor must be routed with the phase conductor(s) to reduce the impedance of the fault path.

4-4

A SAFETY GROUNDING EXAMPLE



SIZE – T0 CARRY FAULT CURRENT.

LOCATION – TO MINIMIZE FAULT PATH INDUCTANCE.

The electronic equipment is in a metal chassis and AC powered. The exposed metal chassis might become energized from the AC power source, and therefore, the chassis should be safety grounded. The grounding conductor must be routed with the AC power conductors, to reduce the inductance of the fault path loop. The grounding conductor must be connected to the metal chassis at the load end, and to the grounded neutral of the AC system at the power source end.

4-5

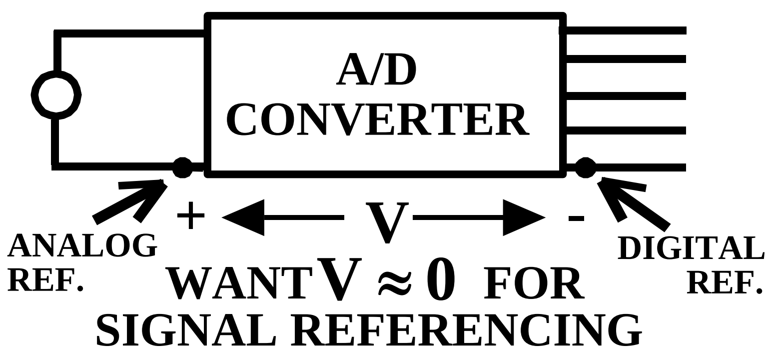
INTERFERENCE GROUNDING – Reduces voltage differences that might cause noise emission or susceptibility problems.

Grounding to reduce interference is completely different from routing to reduce interference.

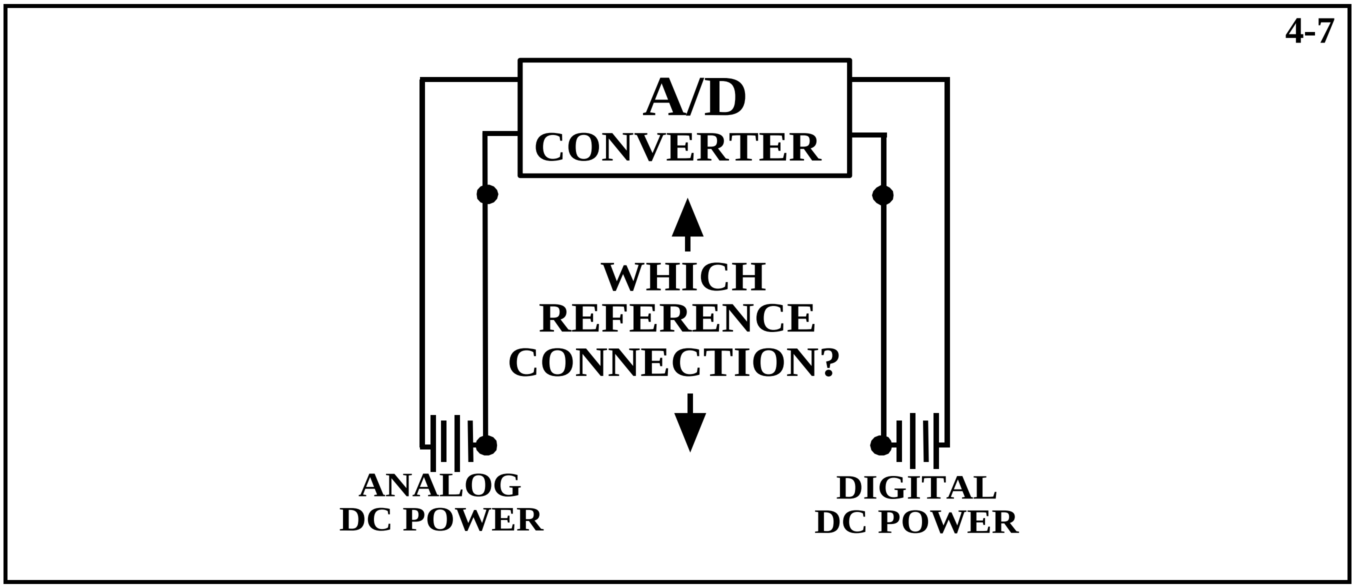
Grounding can be used to reduce interference. Interference reduction by grounding must not be confused with interference reduction by proper signal routing. Routing and grounding are two entirely different concepts.

4-6

INTERFERENCE GROUNDING EXAMPLE

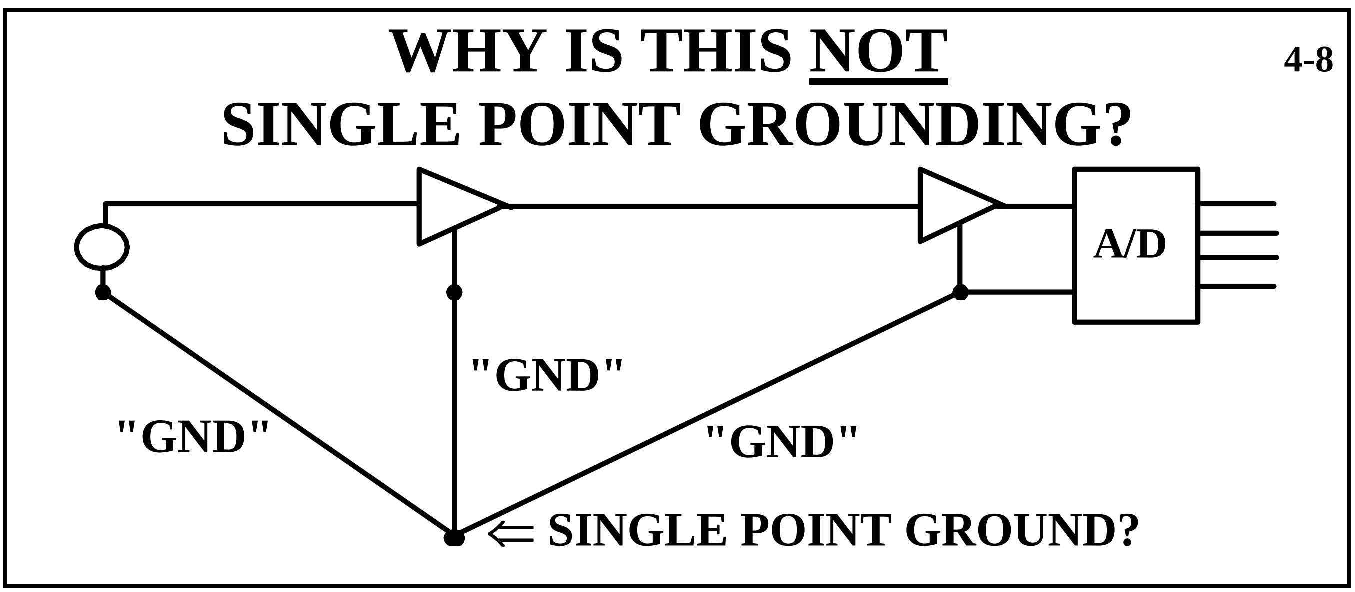


An analog to digital (A/D) converter is a good example of grounding to reduce an interference problem. The analog and digital references should be at the same voltage, to reduce the CM noise voltage applied to the analog input. To reduce the CM voltage, the two references are bonded together by a conductor that should carry no objectionable current under normal operating conditions. An interference grounding conductor is similar to a safety grounding conductor, because both reduce a voltage difference while carrying essentially no current.



Should the interference grounding connection be placed close to the A/D converter or close to the DC power supplies? The two DC power supplies do not need to operate at the same reference potential. However, the A/D converter needs the analog and digital circuits at the same reference potential to minimize the CM noise applied to the converter. So the reference connection must be placed close to the A/D converter.

Would a second reference connection near the DC supplies be helpful? NO! If two or more connections exist between the analog and digital circuits, then the low frequency (kHz) currents can flow between the two circuits using these two connections.



This is not single point grounding. The three conductors labeled "GND" each carry a significant amount of signal current. The “GND” conductors are actually routing conductors and not true grounding conductors. This arrangement increases each of the signal loop areas. For single point grounding to be effective, the grounding conductors must not carry any significant amount of the signal currents.

5-1

5. INTERFERENCE COUPLING MECHANISMS & EQUIVALENT CIRCUITS

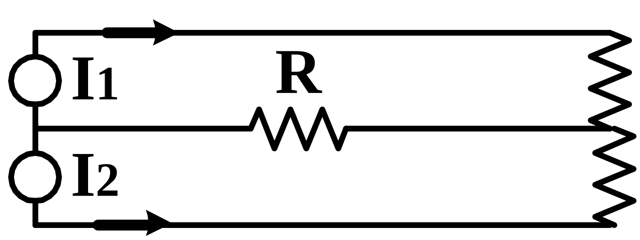
CONDUCTIVE
ELECTROMAGNETIC
MAGNETIC (MUTUAL INDUCTANCE)
ELECTRIC (MUTUAL CAPACITIVE)

Electric noise problems are often described as if there is an endless list of different problems. For example, electrical noise can be caused by arcing relay contacts, fluorescent lights, digital clock circuits, citizen band transmitters, electrostatic discharge, arc welding, switch mode power supplies, lightning, etc. All of these problems are examples of one or more of the four basic noise coupling mechanisms: conductive, electromagnetic, magnetic and electric. Evaluating noise problems in terms of these basic coupling processes means there are only 4 different problems that have to be identified and fixed.

CONDUCTIVE COUPLING

5-2

COMMON IMPEDANCE COUPLING
REQUIRES TWO OR MORE CONDUCTIVE CONTACTS



EXAMPLES

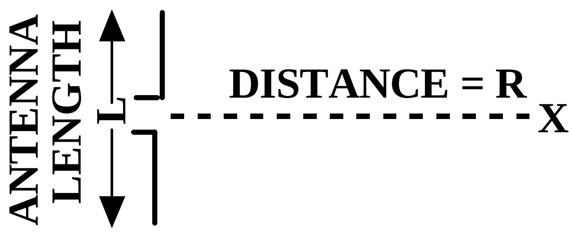
*AC OR DC POWER LEADS
*GROUNDING CONNECTIONS
*A SHARED SIGNAL PATH

Conductive coupling requires at least two contacts between the noise source and the susceptible circuit. One contact carries the noise current **from** the source and the other contact **returns** the noise current to its source. These contacts are usually metal wires. Occasionally nonmetal conductors, such as sea water, battery electrolyte or Earth, are involved.

Conductive coupling is also called **common impedance coupling**. This implies that both the noise current and the susceptible current flow through the same impedance.
If one part of the noise coupling path occurs through a wire but another part of the path is through a stray capacitance, the coupling mechanism is considered to be electric field or capacitive.

5-3

ELECTROMAGNETIC COUPLING REQUIRES A DISTANCE > WAVELENGTH.

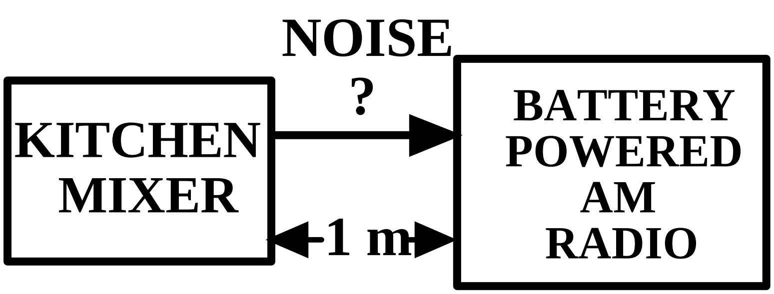


FIELDS VARY AS:
1/R FOR EM WAVE
AND
$1/R^2$ & $1/R^3$ FOR ELECTRIC & MAGNETIC FIELDS.

The electric and magnetic fields produced by an antenna (noise source) vary with distance from the antenna in three ways: 1/R, $1/R^2$, and $1/R^3$. The $1/R^2$ and $1/R^3$ terms are associated with the electric and magnetic energy stored near the antenna. The 1/R terms are associated with the electromagnetic energy **radiated** from the antenna (the far field). For distances $R < \lambda$, either the electric field or the magnetic field dominates, depending on the type (dipole or loop) of antenna. For the radiated electromagnetic wave to be the dominant effect, the minimum distance must be $R > \lambda$.

WHICH NOISE COUPLING MECHANISMS ARE POSSIBLE?

5-4



CONDUCTIVE: REQUIRES 2 CONTACTS

EM WAVE: REQUIRES DISTANCE > λ

Since there are **no wires** connecting the battery powered radio to the mixer, conductive coupling is not possible.

For electromagnetic radiation to dominate, the distance through the air over which the energy couples must be > one wavelength. To determine the wavelength, the noise coupling frequency must be known. In this case the audible frequencies that are heard are not the coupling frequencies. The coupling frequency is the RF carrier frequency. The AM band is centered near f = 1 MHz. Therefore $\lambda = v/f = 300$ m. The coupling mechanism cannot be electromagnetic, since the distance R = 1 m << λ = 300 m.

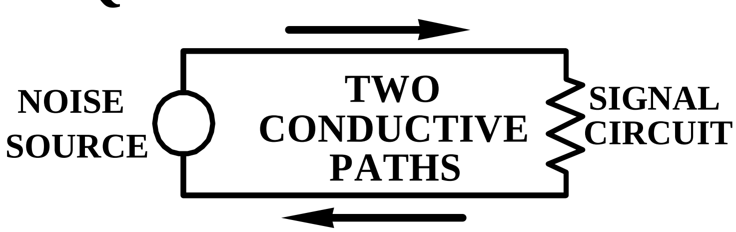
COUPLING MECHANISM	DIAGNOSTIC CLUE	5-5
CONDUCTIVE	TWO METAL CONTACTS	
ELECTRO-MAGNETIC	DISTANCE > λ	
MAGNETIC	(dV/dt)/(dI/dt) << 377 Ω	
ELECTRIC	(dV/dt)/(dI/dt) >> 377 Ω	

In order to predict or fix electrical noise problems, the location of the noise coupling and the dominant coupling mechanism must be known. Each particular coupling mechanism has certain characteristics or clues that aid in its identification. One of the objectives of this course is to relate these clues to particular coupling mechanisms so that a logical strategy can be used to diagnose noise problems, rather than the inefficient "trial and error" method. This figure indicates one clue for each mechanism. Additional clues will be added later.

CONDUCTIVE COUPLING 5-6

REQUIRES TWO OR MORE CONDUCTIVE CONNECTIONS.

EQUIVALENT CIRCUIT

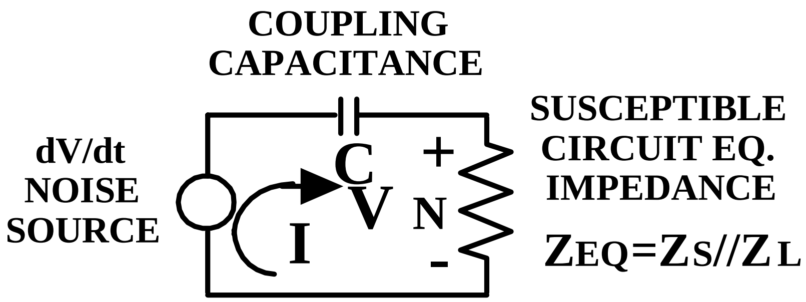


TYPICAL PATHS:

1. POWER (AC OR DC)
2. SIGNAL LEADS
3. GROUNDING CONNECTIONS

Conductively coupled noise is the most common of the four coupling mechanisms. For conductive coupling to occur there must be at least one metallic path to carry the noise current from the source to the susceptible circuit and at least one metallic path to return the noise current to its source. Conductive coupling has the simplest equivalent circuit of the four, but conductive coupling is still difficult to diagnose. The difficulty with conductive coupling is determining which two wires, out of a large number of possible wires, is actually carrying the noise current. If the correct two wires cannot be identified, then all of the wires may have to be filtered.

CAPACITIVE COUPLING EQUIVALENT CIRCUIT 5-7



$$I \approx C\,dV/dt$$

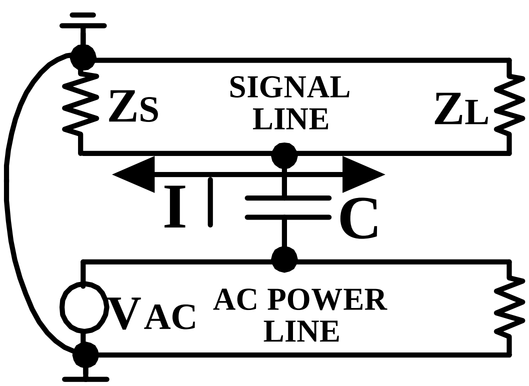
OR

$$I \approx \omega C V$$

$$V_N \approx I Z_{EQ}$$

For capacitive (electric field) coupling to occur there must be: (1) a source of the electric field, that is a time varying voltage dV/dt; (2) a way to couple the electric field to an adjacent circuit, that is a mutual capacitance; (3) a susceptible circuit impedance across which the objectionable noise voltage is developed; and (4) a path by which the capacitively coupled current, I = CdV/dt, can return to its source. The equivalent circuit for all capacitively coupled noise problems contains these same four essential parts.

CAPACITIVE COUPLING EXAMPLE 5-8



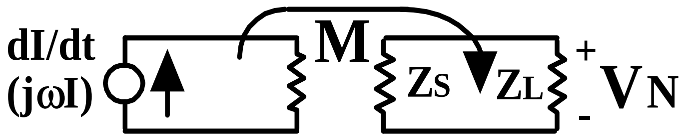
$$Z_{EQ} = Z_S // Z_L$$

$$V_{NOISE\ COUPLED} \approx \omega C \left[\frac{Z_S Z_L}{Z_S + Z_L}\right] V_{NOISE\ SOURCE}$$

LARGE $Z_S//Z_L$ INCREASES CAPACITIVE COUPLING

Assume that an AC power line runs parallel to a signal line. Two parallel wires form a capacitor. The time varying AC voltage can drive a current, CdV/dt, through this capacitance into the signal circuit. The signal circuit has been modeled as source and load impedances connected by wires of zero impedance. (This simplified model works surprisingly well, even for some MHz frequency noise problems.) The signal source and load impedances are connected in parallel, as viewed by the capacitively coupled noise current. When evaluating the equivalent impedance of a circuit subjected to capacitive coupling use $Z_{EQ} = Z_S//Z_L$. The higher the value of Z_{EQ}, the more troublesome the capacitively coupled noise.

INDUCTIVE COUPLING EQUIVALENT CIRCUIT 5-9



$$V_{INDUCED} \approx \omega MI$$

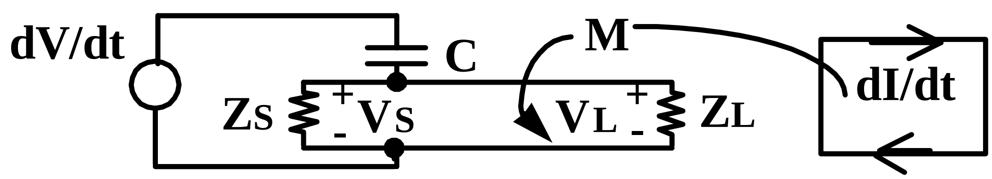
$$V_N \approx \omega MI\{Z_L/(Z_S + Z_L)\}$$

MAGNETIC COUPLING IS INCREASED BY:

1. FAST SWITCHING CURRENT;
2. LARGE LOOP AREAS;
3. $Z_L >> Z_S$.

For inductive (magnetic field) coupling to occur there must be: (1) a source of time varying magnetic field, that is a time varying current dI/dt; (2) a way to couple the magnetic field to another circuit, that is a mutual inductance; and (3) an impedance in the susceptible circuit across which some fraction of the induced noise voltage can appear. Notice that magnetic coupling does not require any metallic connections between the two circuits. Magnetic coupling is worse for circuits with large loop areas and a large load impedance Z_L.

COMPARE NOISE VOLTAGE AT SOURCE AND LOAD TO DETERMINE MECHANISM 5-10



$$V_S/V_L \approx 1 \Rightarrow \text{CAPACITIVE}$$

$$V_S/V_L \approx Z_S/Z_L \Rightarrow \text{INDUCTIVE}$$

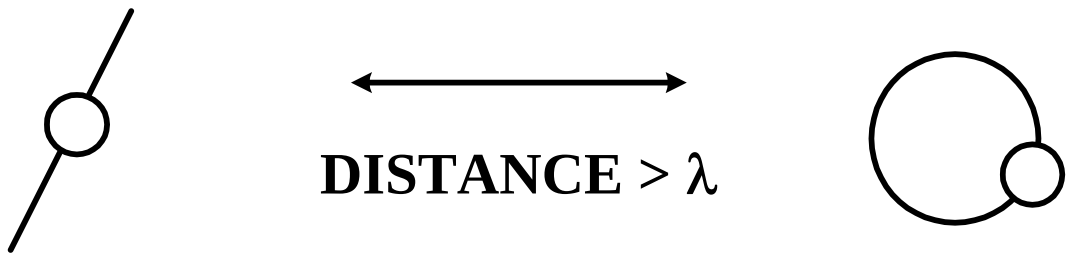
$$V_S \text{ \& } V_L \text{ OUT OF PHASE} \Rightarrow \text{INDUCTIVE}$$

The susceptible circuit is represented by Z_S and Z_L. CdV/dt represents a possible source of electric field coupled noise and MdI/dt represents a possible source of magnetic field coupled noise. With capacitive coupling, the noise voltages across the source and load impedances are nearly equal in magnitude and nearly in-phase. With inductive coupling, the source and load noise voltage amplitudes are proportional to the source and load impedance values respectively, and the two voltages are approximately 180° out-of-phase for resistive impedances. These differences in the victim circuit between capacitively and inductively coupled interferences may allow correct diagnosis of the coupling mechanism without having to identify the source of the coupling.

5-11

EM WAVE COUPLING EQUIVALENT CIRCUIT

TRANSMIT “ANTENNA” **RECEIVE “ANTENNA”**



The equivalent circuit for electromagnetic wave coupling involves a transmitting antenna, a receive antenna, and a separation distance greater than one wavelength. The receive antenna must be in the “far field” of the transmit antenna. If the receive antenna is in the near field, then the dominant interference coupling will be either electric or magnetic field coupling.

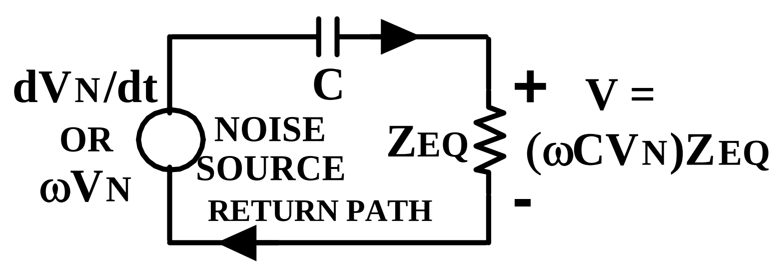
6-1

6. Externally Added Electric-Field Shielding

For externally added shielding techniques the shielding metal is NOT part of the signal current path. Externally added shielding should only be used when self shielding is inadequate or it is too late in the design cycle to employ self shielding.

6-2

CAPACITIVE COUPLING EQUIVALENT CIRCUIT



$Z_{EQ} = Z_S//Z_L$, SUSCEPTIBLE CIRCUIT EQ. IMPEDANCE

The equivalent circuit for a capacitively (electric field) coupled noise problem requires a time varying voltage source, dV_N/dt, to generate the electric field. A mutual capacitance, C, is required to couple the electric field to the susceptible circuit represented by the impedance $Z = Z_S//Z_L$. The induced current CdV_N/dt creates a noise voltage, V, across Z. The noise current requires a return path back to its source.

6-3

DIAGNOSING CAPACITIVE COUPLING

1. HIGH Z_{EQ} SIGNAL CIRCUIT
2. SMALL SIGNAL RESOLUTION LEVEL
3. HIGH NOISE VOLTAGE
4. FAST SWITCHING VOLTAGE
5. EXPOSED METAL SURFACES
6. FLOATING METAL NEARBY
7. NOISE AFFECTED BY PEOPLE OR CABLE LOCATION

The equivalent circuit for capacitive coupling indicates which parameters are critical to this mechanism. The most important parameter is the parallel impedance, $Z_{EQ} = Z_S // Z_L$, of the susceptible circuit. This impedance value can usually be easily determined. The minimum signal voltage resolution level is the second key indicator that capacitive coupling might be a problem. The voltage level and frequency (or switching time) of nearby circuits are additional indicators. Closely spaced signal and noise conductors or metal structures with significant surface areas can be the cause of undesired mutual capacitance.

6-4

REDUCING CAPACITIVE COUPLING

1. REDUCE SIGNAL IMPEDANCE (FILTER SIGNAL CIRCUIT)
2. REDUCE NOISE VOLTAGE
3. REDUCE NOISE FREQUENCY
4. REDUCE MUTUAL CAPACITANCE
5. BREAK NOISE CURRENT RETURN PATH
6. USE CAPACITIVE (ELECTRIC FIELD) SHIELDING

The capacitively coupled equivalent circuit indicates which parameters contribute to the problem. These are the same parameters that must be changed to reduce the problem. To obtain a 20 dB reduction in the noise level, one of the equivalent circuit parameters must be changed by a factor of 10 in the right direction. For example, reduce the noise voltage source by 10, reduce the mutual capacitance by 10, or reduce the susceptible circuit impedance by 10.

6-5

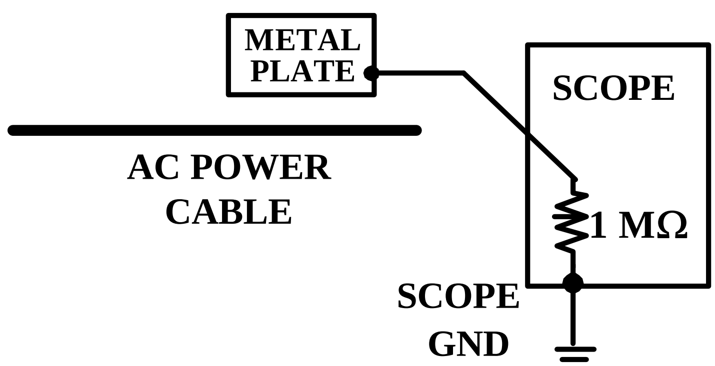
DEMONSTRATION

DIAGNOSING AND REDUCING A CAPACITIVELY COUPLED NOISE PROBLEM

The capacitively coupled noise problem shown in this demonstration contains all of the essential parameters of any "real world" problem. The parameters that contribute to the demonstrated problem are easier to see than in a "real world" problem, because there is less camouflage. This is a good problem on which to practice your noise diagnostic skills.

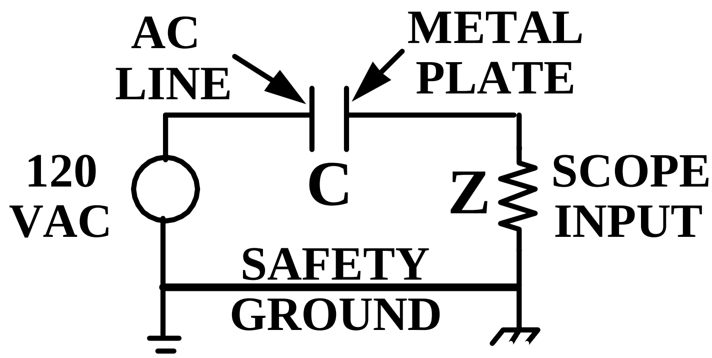
PHYSICAL ARRANGEMENT

6-6



Assume that the metal plate is one-half of a capacitive distance measuring sensor. The other half of the sensor is not present. The scope represents the signal amplifier. Noise at 60 Hz from a nearby AC power cord shows up at the scope input. The objective is to determine how and where this noise energy gets into the system.

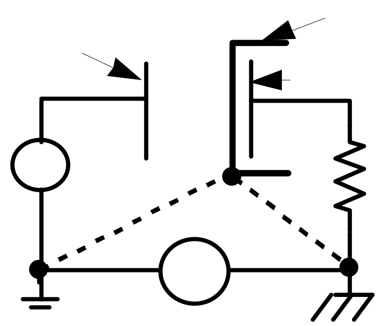
EQUIVALENT CIRCUIT 6-7



If the correct coupling mechanism has been determined, then the equivalent circuit for that mechanism should be able to explain the noise symptoms observed. The electric field source is the 120 VAC. The mutual capacitor is formed by the AC line and the metal plate. The induced current causes a noise voltage to appear across the 1 MΩ scope input impedance. The noise returns to its AC source using the safety ground connection to the scope.

The capacitive coupling equivalent circuit does seem to fit the circumstances of this demonstration.

WHICH SHIELD CONNECTION? 6-8



The capacitive shield must be placed somewhere between the two "plates" of the mutual capacitor. The shield is usually placed closest to the susceptible circuit. The more difficult question is where to connect the shield? The shield connection needs to enable the intercepted noise current to return to its source, but the shield connection must also keep the voltage on the shield the same as the reference of the circuit being protected. In this demonstration the shield should be connected to the chassis of the scope. The scope chassis is the signal voltage reference. The safety ground connection to the scope chassis provides a path for the noise current to return to the neutral of the AC power system. If the shield were connected directly to the neutral, then any voltage difference between the neutral and the scope chassis would capacitively couple into the signal circuit.

6-9

CAPACITIVE SHIELDING OBJECTIVES

1. INTERCEPT NOISE CURRENT WITH THE SHIELD.

2. RETURN CURRENT BACK TO ITS SOURCE.

3. KEEP THE SHIELD AT THE SAME VOLTAGE AS THE SIGNAL BEING PROTECTED.

The objective of capacitive shielding is to intercept the noise current before it gets into the susceptible circuit, and return this current back to its source, without letting it pass through the circuit. The purpose of the shield is not to stop the current, it is to intercept and reroute the current.

If the capacitive shield is placed around the susceptible circuit as opposed to the noise source, then the shield must be at the same voltage as the reference of the circuit being protected. This is necessary to prevent the shield from becoming a source of capacitively coupled noise for the circuit that it is intended to protect.

6-10

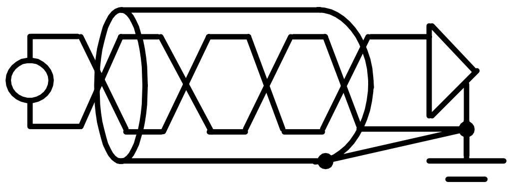
IF THE CAPACITIVE SHIELD SURROUNDS THE SUSCEPTIBLE CURRENT, THEN CONNECT THE SHIELD ONCE TO THE GROUNDED REFERENCE OF THE CURRENT BEING PROTECTED.

This general rule is easy to follow, but is only valid about 85% of the time. In some situations the shield isn't placed around the susceptible circuit, it is placed around the noise source. In a few cases, the circuit being shielded does not have a grounded reference. If the concepts of intercepting, bypassing, and referencing are applied correctly, then the proper shield connection can be logically deduced for situations not covered by this general rule.

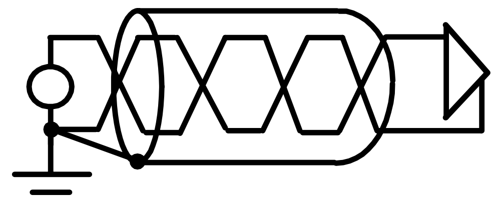
CONNECT THE CAPACITIVE SHIELD WHERE THE SIGNAL REFERENCE IS GROUNDED

6-11

GROUNDED RECEIVER, FLOATING SOURCE.



FLOATING RECEIVER, GROUNDED SOURCE.

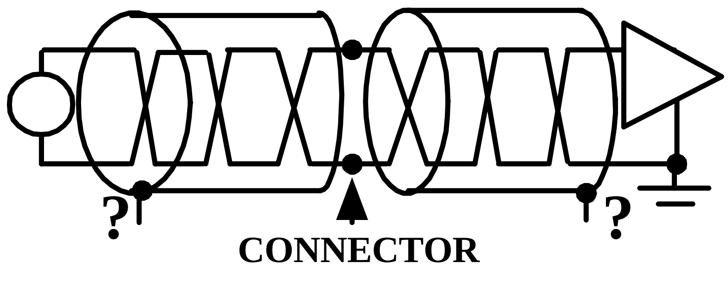


For the example on the left, the capacitive shield should be connected to the grounded reference of the amplifier. This is where the signal reference is grounded.

For the example on the right, the capacitive shield should be connected to the grounded reference of the signal source. This is where the signal reference is grounded in this case. The electric field shield connection is determined by where the signal being protected is grounded.

6-12

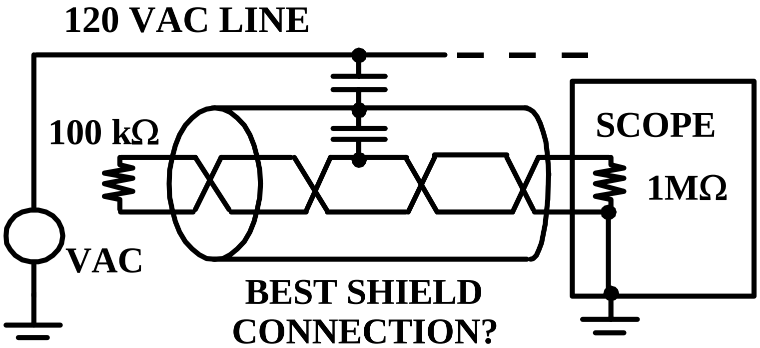
WHERE TO CONNECT THE TWO SHIELDS?



ONE CURRENT ⇒ ONE SHIELD

A shield exists on each half of the signal cable. Often the shield on the receiver end is connected to ground at the receiver, and the shield on the signal source end is connected to ground at the source. This is not the best approach. This is not a situation where there are two electric field (capacitive) shields and each one requires a grounding connection. Because there is only one continuous current to be protected, the two shield "halves" should be bonded together at the connector to form one continuous shield. The one shield should be grounded wherever the current being protected is grounded, that is at the receiver end for this example.

CAPACITIVE SHIELDING DEMONSTRATION



6-13

CONNECT A <u>CAPACITIVE</u> SHIELD <u>ONCE,</u> WHERE THE SIGNAL CURRENT BEING PROTECTED IS GROUNDED.

60 Hz noise is received at the scope input. This frequency is too low for the coupling mechanism to be electromagnetic waves. There are no conducted sources of noise because no "outside" wires connect to this signal circuit. Magnetic field coupling is not likely because the signal loop mutual inductance has been reduced by the use of twisted wires. The 100 kΩ source impedance is a strong indicator that capacitive coupling is the cause of the noise in this case. The floating electric field shield is another clue that capacitive coupling may be the problem.

This noise can be significantly reduced by connecting the shield to the chassis of the scope. The scope chassis is the point at which the signal current reference is connected to ground.

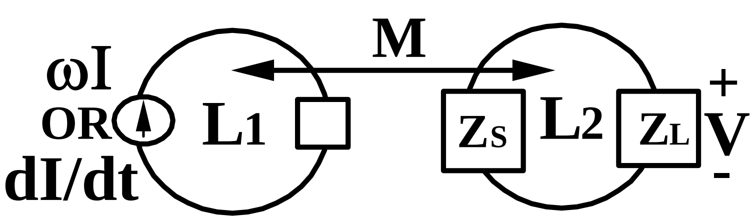
7-1

7. Externally Added Magnetic-Field Shielding

Externally added magnetic-field shielding requires either a high magnetic permeable material or magnetic-field frequencies exceeding several hundred kHz. Self shielding is usually a much better approach.

7-2

INDUCTIVE COUPLING EQUIVALENT CIRCUIT



$$V(t) \propto M dI/dt$$

$$V(\omega) \approx \omega M I Z_L/(Z_S+Z_L)$$

MUTUAL INDUCTANCE (MdI/dt) IS OFTEN MISDIAGNOSED AS A RESISTANCE (RI) PROBLEM.

Inductive (magnetic) coupling requires a time varying current dI/dt to generate the magnetic field and a mutual inductance between two loops. The noise voltage across the load impedance of the susceptible circuit is proportional to the value of the load impedance Z_L.

7-3

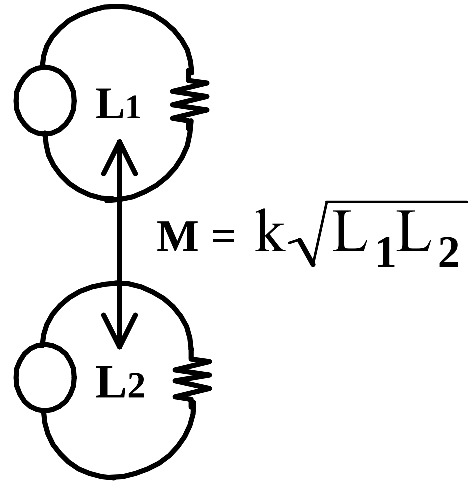
TO REDUCE MUTUAL INDUCTANCE:

DECREASE LOOP AREAS

INCREASE SEPARATION

ADD MAGNETIC SHIELDING:

1. HIGH μ MATERIAL FOR kHz
2. GOOD CONDUCTOR FOR MHz



Mutual inductance is determined by $M = k\sqrt{L_1 L_2}$, where k is the coupling coefficient and L_1 and L_2 are the self inductances of the two coupled loops. The best way to reduce mutual inductance is to reduce either or both self inductances by decreasing the loop areas. The coupling coefficient can be reduced by orthogonal orientation of the two loops, increasing the separation between the loops, or placing shielding material between the two loops. Low frequency (kHz) magnetic shielding is often expensive and ineffective, so this technique should be reserved for "acts of desperation".

7-4

MAGNETIC FIELD EXTERNAL SHIELDING:

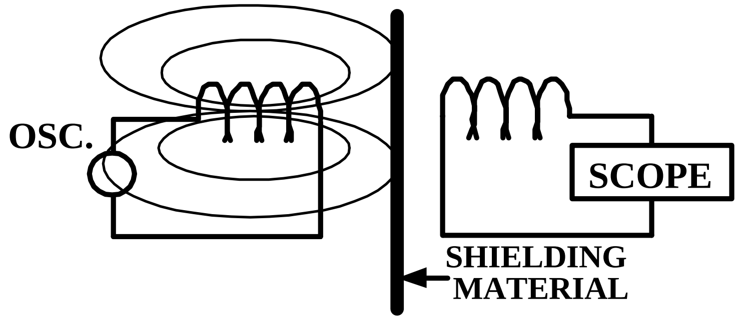
1. SHUNTING – CHANGE FLUX PATH WITH A HIGH μ MATERIAL.

2. REFLECTION – CREATE OPPOSING FLUX WITH EDDY CURRENTS.

The best magnetic shielding technique is self shielding. When self shielding is not possible or is inadequate, then extra material can be added to give additional magnetic shielding. Materials with a high magnetic permeability (μ) can divert the magnetic flux away from areas to be protected. Iron, nickel and cobalt are three high permeability materials. Another possibility is to allow the magnetic field to induce eddy currents in a good conductor. These eddy currents produce their own magnetic field that opposes the rate of change of the original magnetic field.

7-5

DEMONSTRATION OF MAGNETIC FIELD EXTERNAL SHIELDING



Two coils are oriented such that the magnetic field created by one coil couples to the other coil. Various shielding materials can be placed between the two coils to determine their magnetic shielding effectiveness. The performance of a material will depend on its ability to divert the magnetic field with a high μ or to create eddy currents. High μ materials provide shielding from DC to about 10-50 kHz, whereas good conductors allow eddy current shielding above about 20 kHz.

8-1

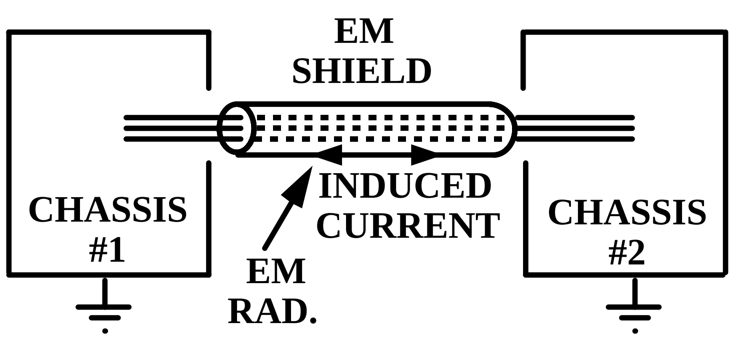
8. Externally Added Electromagnetic Wave Shielding

Electromagnetic waves cannot penetrate a totally closed metal surface at least 10 skin depths thick.

The best way to reduce far-field electromagnetic waves is to reduce the near electric and magnetic fields. Self shielding or externally added shielding can be used to reduce electromagnetic waves. When using externally added shielding the conducting material must totally surround the region in order to keep the electromagnetic energy either in or out.

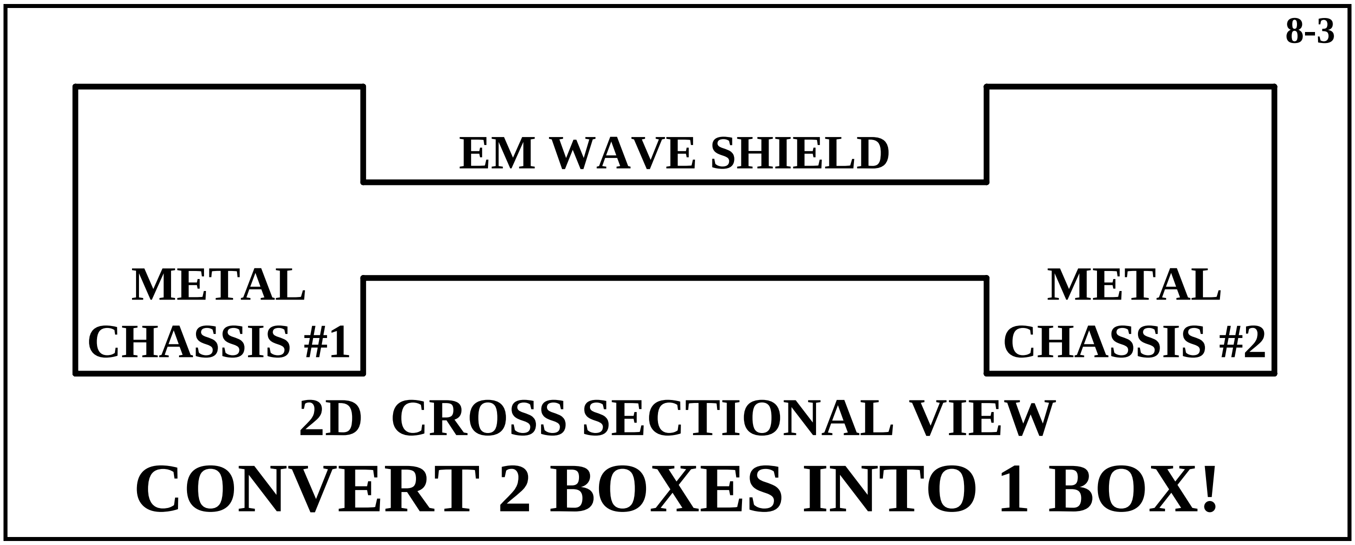
HOW TO CONNECT THE ELECTROMAGNETIC SHIELD ON A CABLE?

8-2

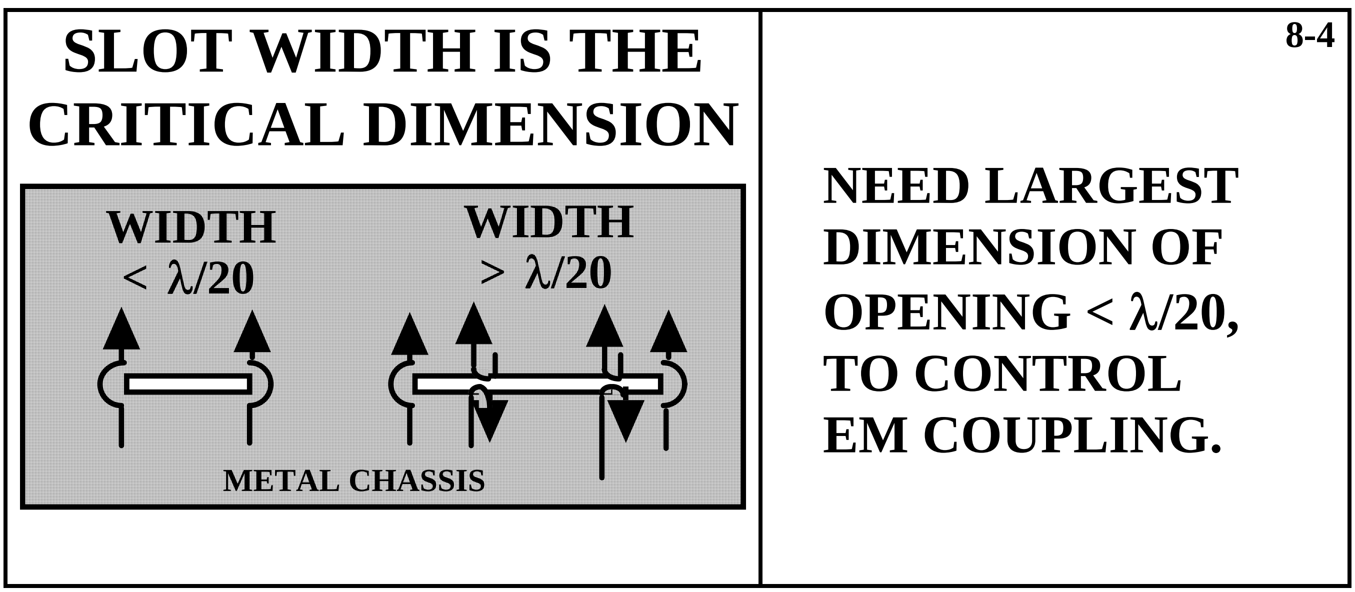


Assume that an external source forces HF currents to flow on the outside surface of the cable shield. This will not be a susceptibility problem as long as the currents remain on the outside of the shield and on the outside of the metal chassis. If the shield has a 360° connection to the metal chassis on each end of the cable, then the HF currents have no easy point of entry into the chassis. This assumes that no apertures are present in the external walls of either chassis. The key to making an EM shield effective above 100 MHz is the quality of the 360° peripheral connections at all disconnection points along the cable.

The effectiveness of the shield is indicated by the shield transfer impedance. This figure of merit is discussed later in this chapter.



The purpose of the electromagnetic wave shield on a cable between two metal chassis is to convert the two boxes into one box. If a totally closed metal surface several skin depths thick surrounds a volume, then high frequencies cannot pass into or out of this volume. EM wave shielding relies on a closed conducting surface and does not involve grounding.



How large can an aperture become and still control electromagnetic leakage? Assume that the longest dimension of the aperture is perpendicular to the noise current flowing on the chassis surface, as shown in the figure above. If the aperture WIDTH < $\lambda/20$, then the noise current can easily flow around the edges of the slot. In this case minimal coupling through the aperture occurs. As the aperture WIDTH exceeds $\lambda/20$, the coupling increases. Once the aperture WIDTH equals or exceeds $\lambda/2$, no shielding should be assumed.

9. A Review of Key Concepts

1. SIGNAL ROUTING

Each current returns to its source.

There are conduction currents (free electrons) moving in metals and displacement currents (bound charges) moving in dielectric materials.

Current takes the path of least impedance, not least resistance.

Above 10 kHz, current takes the smallest loop area path.

Below 1 kHz, current takes every possible path.

Electromagnetic interference can result if only 0.1% of the signal current takes an unintended path.

For wiring, the distributed LC = $\mu\varepsilon$ = a constant (usually).

Excessive wiring self-inductance is indicated by:

1. **Excessive signal path loop area;**
2. **Low wiring self capacitance; or**
3. **A ringing waveform.**

Don't confuse signal routing with signal grounding.

Impedance imbalance causes electrical energy to convert between differential and common modes.

2. BANDWIDTH

Most of the energy in a periodic pulse waveform is below $f = 1/(\pi t_r)$.

For signal integrity the bandwidth of concern is usually DC to $1/(\pi t_r)$.

For electromagnetic emissions the bandwidth of concern is typically DC to $10/(\pi t_r)$.

3. RESONANCE

Most electromagnetic interference problems involve resonance.

Near resonance current paths can have either unusually large or unusually small impedance depending on whether the resonance is parallel or series.

Resonance can cause currents to take an unintended path.

At resonance in a low loss circuit, the currents and the voltage differences can be 100 times larger than expected.

4. GROUNDING

Electrical systems are grounded for:

1. **Safety;**
2. **Interference Reduction.**

No significant current flows through a grounding conductor under normal conditions.

The signal grounding conductor is NOT the same as the signal routing conductors.

Don't confuse signal routing with signal grounding.

For MHz noise frequencies, grounding is not as important as field containment.

There are two grounding techniques:

1. **Ground Grid – uses a low resistance to "short out" the ground voltage difference;**
2. **Isolated Grounding (Single Point Grounding) – avoids connecting to the ground voltage difference.**

The ground grid is best for safety under high current faulting or lightning conditions.

Isolated (single point) grounding is best for reducing kHz noise.

5. NOISE COUPLING MECHANISMS

Coupling Mechanism	Identifying Feature
1. Conductive	*Two metal contacts*
2. Electromagnetic Wave	*Distance > Wavelength*
3. Electric Field (Capacitive)	*dV/dt,* $Z > 377\ \Omega$
4. Magnetic Field (Inductive)	*dI/dt,* $Z < 377\ \Omega$

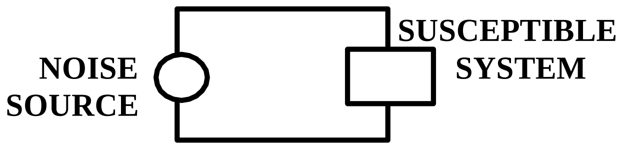
Conductive coupling can occur when two currents flow through the same impedance (common impedance coupling).

Currents generate magnetic fields.

Voltage differences generate electric fields.

Conductive Coupling

Equivalent Circuit

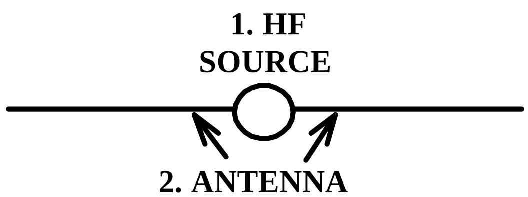


Filter Options

1. DM filter
2. Improve balance
3. Isolate from ground

Electromagnetic Wave Coupling

Equivalent Circuit

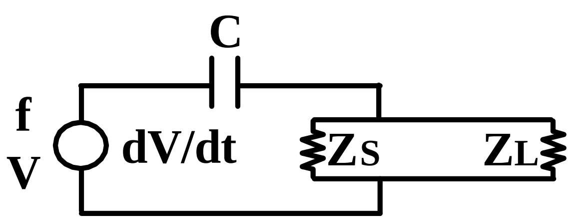


Solutions

1. Reduce intensity & bandwidth of source
2. Block current from antenna (CM Filter)
3. Keep metal antenna parts at the same RF voltage

Capacitive (Electric Field) Coupling

Equivalent Circuit

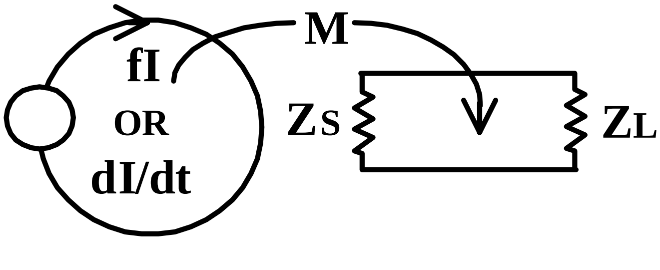


Solutions

1. Reduce Z_S or Z_L
2. Reduce f, V, or C
3. Disconnect return
4. Use electric-field shielding

Inductive (Magnetic Field) Coupling

Equivalent Circuit



Solutions

1. Reduce loop area
2. Reduce f or I
3. Increase separation
4. Use magnetic shielding

6. Filtering

There are two filter strategies

1. **Current Blocking**

   Add a $Z_{series} >> (Z_{load} + Z_{source})$

2. **Current Diverting**

   Add a $Z_{shunt} << (Z_{load} // Z_{source})$

The mutual inductance must be minimized for shunt-mounted capacitors.

A series ferrite bead can be effective when

$Z_{bead} >> (Z_{source} + Z_{load})$.

7. Field Containment

Electric and magnetic fields can be contained by

1. **Self-shielding**
2. **Externally added shielding.**

For self-shielding:

1. **The return current path must surround the outgoing current path, as for a coaxial cable; and**
2. **The metal involved <u>is</u> an intentional part of the signal path.**

For externally added shielding:

1. **The metal involved <u>is</u> <u>not</u> part of the signal path;**
2. **The shielding material and electrical connection may be different for electric-field, magnetic-field, and electromagnetic-wave coupling mechanisms.**

8. Diagnostic Techniques

Voltage probes, electric- and magnetic-field probes, and clamp-on current probes are effective diagnostic tools.

The values of the signal source and load impedances help to determine the most likely dominant noise coupling mechanism.

When diagnosing a noise problem:
First – determine where the noise couples into or out of the equipment,
Second – determine how the noise is coupled (which noise coupling mechanism dominates).

Disconnecting the load on a noise emitting circuit will usually indicate whether the dominant coupling is magnetic fields caused by the current or electric fields caused by the voltage difference of the noise source.

Current loop areas are associated with magnetic-field (mutual inductance) coupling and metal surface areas are associated with electric-field (mutual capacitance) coupling.

If people affect the noise level, the coupling mechanism is either electric fields or electromagnetic waves.

Electrically "floating" metal usually increases electric-field and electromagnetic-wave coupling and decreases magnetic-field coupling.

9. DC Power Distribution

Do not allow different DC voltage planes to overlap one another. For example, the +5 V and +15 V planes should not overlap. Bipolar DC voltage planes, such as +15 V and -15 V, should overlap. Overlapping voltage planes allows noise to capacitively couple between the two power distribution buses.

Maximize the distributed capacitance in the DC power bus. For digital circuits, use parallel power and return planes with a Z_O < 1 Ω.

A three-layer stack up of planes, such as return-power-return, can provide excellent field containment and reduce EMI caused by power bus resonances. The two return planes must be connected by closely spaced vias around the edges. The typical two-layer arrangement of power and return planes provides very poor electric and magnetic field containment.

Minimize the series inductance of any lumped decoupling capacitors. For boards with power and return planes, this inductance is caused by the capacitor body, solder pads, microstrip traces, and vias that connect the capacitors to the planes. It is important, but very difficult, to get the total connecting series inductance below 1 nH.

For surface mounted chip capacitors, place the vias in the solder pads. If this is not possible, keep the trace length to each via < 0.1" and the trace width > 0.1".

For boards with power and return planes that have a low distributed inductance, for example planes separated by < 20 mils, each integrated circuit uses all of the decoupling capacitors that

are connected directly to the power and return planes and within a radius equal to the phase velocity times the switching time. Many decoupling capacitors may be shared by several ICs.

Provide at least one ceramic chip decoupling capacitor for each integrated circuit DC power pin. The value of this capacitor usually ranges between 1-100 nF, depending on the amount of peak current switched through this power pin and the switching time.

Provide bulk decoupling (10 - 100 μF) where the DC power comes onto the board and at the output of each voltage regulator and DC-DC converter.

10. Transmission Lines

A trace may need to be treated as a transmission line when the trace length > λ/20, or the propagation delay > (pulse rise time)/4.

Use a Z_o > 40 Ω to minimize the drive current and a Z_o < 120 Ω to reduce emission and susceptibility.

Unintended sharp transitions in the signal level may indicate reflections due to impedance mismatches.

Multiple reflections require two or more locations of impedance mismatch. The time delay between the arrival of successive reflections may indicate the distance D between the two points where the impedance mismatches are located.
D = (phase velocity)(time delay)/2

Grounding and Shielding of Electronic Systems

How to Diagnose and Solve Electrical Noise Problems

A 15-Hour Video Taped Presentation

by
Dr. Tom Van Doren
Professor of Electrical Engineering
Electromagnetic Compatibility Laboratory
University of Missouri-Rolla

Program Description

Most engineers and technicians using or designing electronic systems have not had formal training concerning grounding and shielding techniques. Learning how to solve grounding and shielding problems on the job can be very expensive for the employer and frustrating for the engineer. Most of the electromagnetic and circuit principles involved are simple. However, the complexity of many systems masks the logic and simplicity of possible solutions.

This course presents an organized introduction to fundamental grounding and shielding principles, clarifies troublesome terminology, and demonstrates many techniques for identifying and fixing electrical noise problems. The principles will be described as concepts rather than theoretical equations. The emphasis on concepts will make the course useful for people with a wide range of experiences. Several interference mechanisms and shielding techniques are demonstrated.

Benefits

This course will help you to:

- Use a logical procedure to diagnose and solve electrical noise problems;
- Reduce the time and cost required to meet emission and susceptibility specifications;
- Determine the optimum grounding technique for safety and low noise;
- Recognize that all electrical noise problems are caused by four basic coupling mechanisms; and
- Determine the correct connection for cable shields.

Course Outline and Learning Objectives

(• denotes key topics and € denotes learning objectives)

Session 1: The Path of Least Impedance

- Identifying the current path
- Importance of wiring inductance
- Demonstration - loop area controls inductance

€ Explain why wiring inductance is more important than resistance.

€ Describe how current loop area is related to self inductance.

Session 2: Electrical Noise Coupling Mechanisms

- Conductive coupling
- Magnetic-field coupling
- Electric-field coupling
- Electromagnetic-wave coupling

€ Describe the four noise-coupling mechanisms.

€ List one key indicator for each mechanism.

Session 3: Noise Coupling Equivalent Circuits

- Circuit for each coupling mechanism
- Parameters critical to noise reduction
- Example problems

€ Describe two ways to reduce each of the four coupling mechanisms.

Session 4: Why and How to Ground Electrical Systems

- What is "electrical ground?"
- Reasons for grounding
- Grounding analog and digital circuits
- Reducing ground-loop noise

€ Explain the two reasons for grounding.

€ Explain the difference between a grounding conductor and a return conductor.

Session 5: Signal Grounding Concepts and Examples

- Ground each current only once
- Where to ground a signal
- Misuse of single-point grounding

€ Explain why a signal should be grounded to an external metal enclosure.

€ Describe signal isolation techniques used to avoid ground loops.

Session 6: How to Diagnose Noise Problems

- Ringing, rounding and reflections
- Demonstration - measuring noise
- Influence of circuit impedance

€ Describe one noise symptom for each coupling mechanism.
€ Use the susceptible circuit impedance to identify the most likely coupling mechanisms.

Session 7: Impedance Balancing and Common Mode Rejection

- Common mode and differential mode
- What does impedance balance mean
- Demonstration - CM to DM conversion

€ Recognize the importance of impedance balancing as a noise-reduction technique.
€ Identify causes of circuit imbalance.

Session 8: Filtering Conducted Noise

- Types of filters
- Influence of circuit impedance
- Controlling mutual inductance
- Use of ferrite beads

€ Explain when to use series blocking and shunt diverting filter techniques.
€ Understand the problem with mutual inductance between input and output.

Session 9: Self Shielding - Low Cost Field Containment

- The concept of self shielding
- Self-shielding examples
- Misuse of twisted pair

€ Explain how self shielding works.
€ Describe how self shielding can reduce the use of other shielding materials.

Session 10: Electric-Field Shielding

- Demonstration: an electric-field coupling problem
- Where to ground the shield on a twisted pair cable
- Electric-field shielding examples

€ List several circuit characteristics that help identify electric-field noise coupling.
€ Explain how often and where to ground the electric-field shield on a cable.

Session 11: Magnetic-Field Shielding

- Magnetic-field shunting and reflection
- Demonstration: magnetic-field shielding
- Problems with high permeability materials

€ Identify the frequency ranges over which magnetic-field shunting and reflection are effective.
€ Describe the difficulties with high-permeability shielding materials.

Session 12: Electromagnetic-Wave Shielding

- Shielding against ESD and RF
- 360˚ shield connections
- Reducing leakage through seams
- Dampening chassis resonances

€ Explain why radiation is influenced more by the quality of the shielding connections than by grounding.
€ Describe how to control radiation leakage through seams and openings in a metal chassis.

Session 13: Selecting the Right Cable

- Desirable EMC properties of cables
- Comparing coaxial and twisted-pair cables
- Cable selection examples

€ Explain how to evaluate cable alternatives given the noise-coupling mechanism and the signal bandwidth.

Session 14: Circuit Board Layout - Part I

- Controlling trace inductance
- Avoiding traces crossing gaps in the return plane
- Connector placement to reduce emissions
- DC power distribution
- Sizing and locating decoupling capacitors

€ Recognize trace layouts that have excessive inductance.
€ Design more effective DC power-distribution busses.

Session 15: Circuit Board Layout - Part II

- Component placement
- Signal and power stackup alternatives
- Grounding heat sinks
- High-speed transmission lines

€ Compare the placement of signals on outer layers versus signals between two planes.
€ Determine which nets should be terminated as transmission lines.

The cost of the video taped program, including one detailed set of reproducible notes, is $3500.
If you have any questions about the program, please call Tom Van Doren at 573-341-4097.
To order the video tapes and notes, please send a check or purchase order to:
Van Doren Company
11600 County Road 5180
Rolla, MO 65401

Circuit Board Layout to Reduce Electromagnetic Emission and Susceptibility

A 5-Hour CD or Videotaped Presentation
by
Dr. Tom Van Doren
Professor of Electrical and Computer Engineering
Electromagnetic Compatibility Laboratory
University of Missouri-Rolla

Program Description

The course covers circuit board layout issues that span the frequency range from DC to several GHz. Mixed analog and digital designs, and multilayer boards are emphasized. Most of the concepts and techniques presented are applicable to one- and two-sided board designs. Several key concepts are illustrated with demonstrations. You will also learn techniques for diagnosing electromagnetic interference problems at the board level.

This course shows that the issues of safety, emission, and susceptibility can be used to determine if, where, and how to connect the circuit board to a metal enclosure. Each specific case has its own unique result, but all conclusions are based on the same electromagnetic compatibility principles.

Benefits

This course will help you to:

- Design or manufacture electronic equipment
- Design printed circuit boards
- Design metal enclosures for circuit boards
- Select connectors and cables attached to circuit boards
- Design integrated circuits and packages
- Design filters to reduce conducted emissions
- Select heat sinks for integrated circuit packages
- Test for electromagnetic compatibility of products containing circuit boards

Learning Objectives

- Explain why wiring inductance is more important than resistance
- Describe how current loop area is related to self inductance
- Explain how resonances worsen circuit board emission and immunity
- Determine which nets should be terminated as transmission lines
- Describe the four noise-coupling mechanisms
- Describe two ways to reduce each of the four coupling mechanisms
- Explain the two reasons for grounding
- Explain the difference between a grounding conductor and a signal return conductor
- Explain why a signal should be grounded to an external metal enclosure

- Explain when to use series blocking and shunt diverting filter techniques
- Understand the problem with mutual inductance between the input and output loops of shunt capacitors
- Recognize trace layouts that have excessive inductance
- Design more effective DC power-distribution busses
- Understand the advantages of alternative layer stackup configurations

Course Outline

Session 1:

1. Introduction
2. Signal Routing and the Path of Least Impedance
3. Transmission Line Effects

Session 2:

3. Transmission Line Effects (cont.)
4. Noise Coupling Mechanisms

Session 3:

5. Circuit Board Grounding Issues
6. Filtering Conducted Noise

Session 4:

7. DC Power Distribution and Decoupling

Session 5:

8. Component Placement and Layer Stackup
9. Chassis, Cable, and System Issues
10. Review of EMC Principles and Board Layout Guidelines

APPENDIX 1 A Review of Background Material
APPENDIX 2 A Summary of EMC Guidelines for Circuit Board Layout

The cost of the CD or videotaped program, including one detailed set of reproducible notes, is $1000.

If you have any questions about the program, contact Tom Van Doren by phone at 573-341-4097 or by email at vandoren@umr.edu. A sample videotape consisting of Session 1 with the accompanying notes is available for review. Please call, email, or write to request the sample tape.

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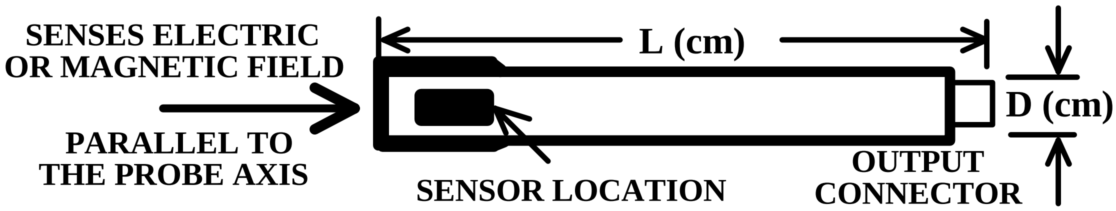
MODELS AVAILABLE AND ORDERING INFORMATION

LOCATE AND SOLVE ELECTRICAL NOISE PROBLEMS WITH THESE PROBES!



EXAMPLE APPLICATIONS:

*Locating the sources of electrical noise.
*Incorrect printed circuit board trace routing.
*Magnetic noise from switch mode power supplies.
*Motor and relay generated noise.
*Use the probe as a noise source to check the susceptibility of a circuit or device.

MAGNETIC FIELD PROBES	FREQUENCY RANGE	SIZE LXD	CONNECTOR TYPE	2004/2005 PRICE
MLF-12	40 Hz - 20 KHz	20 x 1.3	BNC	$130
MLF-11	3 KHz - 300 KHz	19 x 1.3	BNC	$ 95
MHF-21	100 KHz - 20 MHz	19 x 1.3	BNC	$ 95
MHF-22	500 KHz - 50 MHz	19 x 1.3	BNC	$ 95
MHF-23	40 MHz - 400 MHz	19 x 1.3	BNC	$ 95

ELECTRIC FIELD PROBES	FREQUENCY RANGE	SIZE LXD	CONNECTOR TYPE	2004/2005 PRICE
EWB-11	60 Hz - 100 MHz	19 x 1.3	BNC	$ 75
EWB-12	10 MHz - 1000 MHz	15 x 1	SMA	$115

DELIVERY - PROBES CAN BE SHIPPED WITHIN ONE WEEK AFTER RECEIPT OF ORDER. THE PRICE INCLUDES SHIPPING CHARGES.

TO ORDER - SEND A CHECK OR PURCHASE ORDER TO:

VAN DOREN COMPANY
11600 County Road 5180
ROLLA, MO 65401

TO PLACE TELEPHONE ORDERS CALL 573-341-4097

TO FAX A PURCHASE ORDER USE 573-341-4532

OPERATING INSTRUCTIONS FOR ELECTRIC AND MAGNETIC FIELD SENSING PROBES

MODEL NUMBERS: MLF-12, MLF-11, MHF-21, MHF-22, MHF-23, EWB-11 & EWB-12

These probes are tools for locating the sources of magnetically or electrically coupled noise. A coil inside the magnetic probe tip and a metal disk inside the electric probe tip respond to the field component parallel to the probe axis. An oscilloscope or spectrum analyzer is normally used to monitor the output. The probe should be held with the tip within two inches of the suspected source of electrical noise.

WARNING - **POSSIBLE SHOCK HAZARD** - do not use these probes near devices operating at voltages exceeding 200 V. Do not allow the probe to electrically contact any energized device or allow sharp objects to puncture the probe's insulating cover. Make certain that the probe's BNC output connector is properly safety grounded.

These probes normally generate sufficient output voltage to connect directly to an oscilloscope without any need for preamplification. If additional sensitivity is required a spectrum analyzer should be used. The magnetic probe output voltage is proportional to the derivative of the magnetic field. The electric probe output voltage is directly proportional to the electric field.

Currents and voltages generating electrical interference are easily located with these probes. The small physical size of the probe permits a precise location of the noise source. For example, the noise generated by adjacent integrated circuit chips can be individually observed and compared. The probes are not calibrated. They are intended to indicate the relative field strength, such as the field before and after a design change. Most noise detection and reduction procedures do not require an absolute measurement of the field strength.

The maximum cable length connected to any probe operating above 1 MHz should be less than four feet. Longer cables increase the capacitive loading and reduce the maximum operating frequency.

These probes may also be used to test the noise susceptibility of a circuit or device. By driving the probe with a voltage source, a localized magnetic or electric field can be created at the probe tip. Critical circuit functions, such as the voltage on an enable line, can be monitored for interference while the probe generated noise is moved over the circuit to locate susceptible devices or wiring. The maximum voltage applied to the probe should be less than 10 V peak and within the operating frequency range of the probe.