Signal and Noise Measurement Techniques Using Magnetic Field Probes

Douglas C. Smith
Auspex Systems
2300 Central Expressway
Santa Clara, CA 95050
Phone: (408) 566-2157

Abstract: Magnetic loops have long been used by EMC personnel to “sniff” out sources of emissions in circuits and equipment. Additional uses of such probes are presented here that can be very useful to both EMC personnel and circuit designers. Methods are shown for measuring crosstalk and inductive voltage drop along conductors, trace current paths on conducting planes, measure currents, and inject precisely controlled amounts of noise into a circuit. Data is presented in this paper to illustrate usage of some of these methods.

LOOP OPERATION

Equivalent Circuit

Before jumping into interesting uses for magnetic loops, it is instructive to consider a magnetic loop from a circuit point of view. Consider a square loop held adjacent to a current carrying conductor as shown in Figure 1.[1]

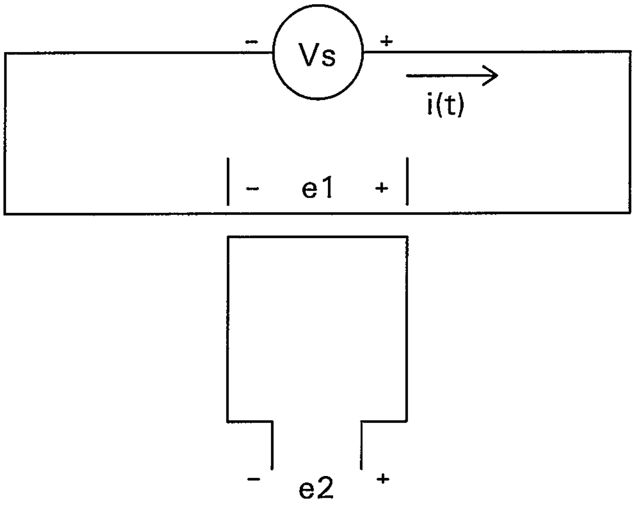

Figure 1. Square Loop and Current Carrying Conductor

For this case, the loop is just made out of bent wire and is a small fraction of a wavelength in circumference at the highest frequency of interest. The inductive voltage drop across the current carrying conductor is:

$$e1 = L \bullet di/dt \qquad (1)$$

where:
L is the inductance per unit length of the conductor

The open circuit induced voltage at the output of the loop is:

$$e2 = M \bullet di/dt \qquad (2)$$

where:
M is the mutual inductance between the conductor and the loop

Note that since M is always less than L, the open circuit output of the loop will have the same waveshape (the di/dt part) as the inductive voltage drop across the driving circuit and represent a lower bound for its magnitude.

Thus, a square loop with one side parallel and close to a current carrying conductor will have an output voltage that is a lower bound estimate of the inductive drop across the wire between the corners of the square loop. This makes square loops more useful than round ones for circuit measurements. A round loop will also give a lower bound estimate, but its output will be lower for the same size loop. Since a round loop gradually pulls away from a planar circuit, an integral equation is necessary to more accurately estimate the inductive drop per unit length along the current carrying conductor.

The Thevenin equivalent circuit for the loop of Figure 1 at its output terminals is shown in Figure 2.[1] This simplified loop model assumes that the presence of the loop does not alter the current in the conductor appreciably. Capacitance between the conductor and the loop is also ignored. These assumptions are reasonable for many measurements. This model yields useful information about how the loop works and suggests some useful measurements that can be made with a magnetic loop on circuits.

If a magnetic loop is held up to a wire carrying a constant current that is swept in frequency, the output will rise with frequency at 20 dB/decade. Above the low pass cutoff frequency formed by the loop self inductance and a 50 Ω load (generally placed on the loop by the need to terminate

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the coaxial cable connecting the loop to a measuring instrument) the frequency response becomes flat. Figure 3 illustrates the components of the loop frequency response.[1]

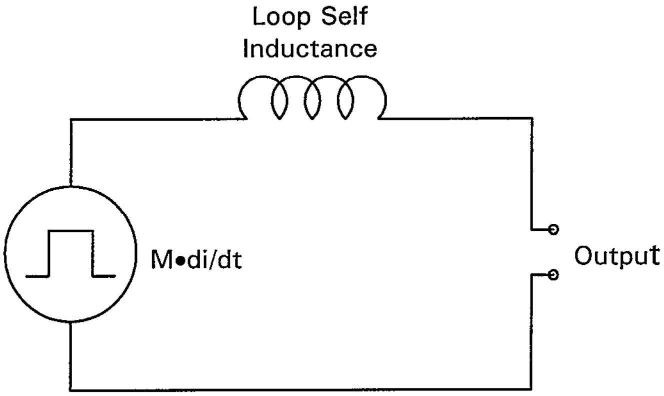

Figure 2. Loop Equivalent Circuit

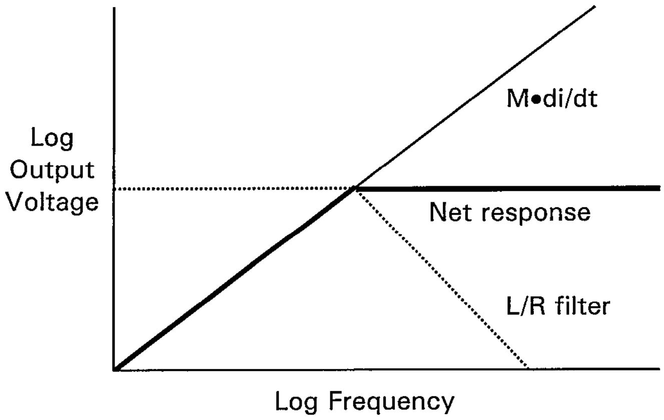

Figure 3. Loop Frequency Response

The frequency response shown in Figure 3 has the same shape as that of a current probe.[2] In fact, a magnetic loop can be used as a current probe with the limitation that the transfer impedance is not known accurately. The transfer impedance must be estimated since the coupling between the loop and circuit is a function of several variables including the distance between the loop and the circuit and the width of the circuit path.

For a 2.5 cm loop, the corner frequency occurs at about 100 MHz. This is due to the fact that the loop inductive reactance ($L \approx 80$ nH for a 2.5 cm loop) is equal to 50Ω at about 100 MHz. The flat region continues until just past 1 GHz where the loop becomes resonant.

Shielded vs. Unshielded Loops

For many EMC applications, shielded loops are used. Figure 4 shows drawings of a pair of shielded loops.[1] The gap in the shield, shown larger in relative size for clarity, prevents shield currents from flowing around the loop yet still permits electric field shielding of the center conductor. If such currents flowed, they would cancel the incident magnetic field to a large extend and voltage would not be developed in the center conductor in response to a magnetic field passing through the center of the loop.

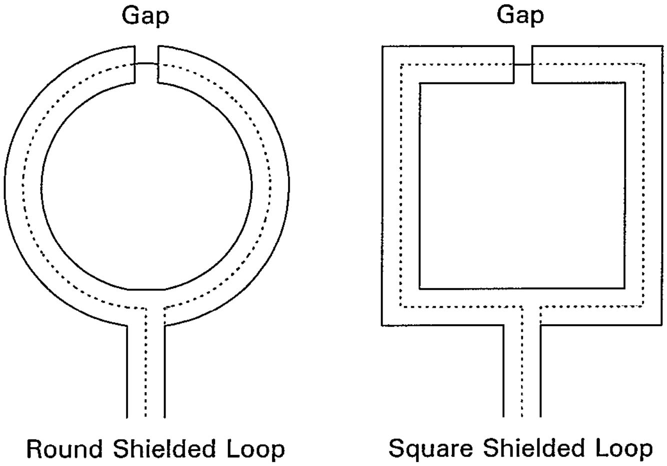

Figure 4. Two Types of Shielded Loops

The uniformity of the field affects how well the electric field shielding works. This is not much of a problem for loops used to measure the magnetic component of plane waves. However, when the loop is held directly against a circuit to measure inductive drop, the fields are not uniform.

If an electric field couples onto one side of the loop with different amplitude than the other side of the loop relative to the gap, different currents will be set up in the two sides of the shield. This will result in different inductive drops being generated in the shield on opposite sides of the gap. Since the mutual inductance between the shield and center conductor is equal to the shield inductance, these unequal voltages will be induced into the center conductor and the electric field shielding will not be very effective.

For the electric field shielding to be effective, it is only necessary for the electric fields to be symmetrical around the gap in the probe shield. This can be seen from the experimental setups shown in Figure 5. In this experiment, an electric field probe is excited by a 20 MHz square wave with a 2 ns risetime. The probe is then placed on each side of the loop and at the center over the gap in the shield. Figures 6, 7, and 8 show the loop output for the electric field probe held at the top of the loop, at the center over the gap, and at the bottom of the loop respectively.

Figure 5. Electric Field Testing of Shielded Loops

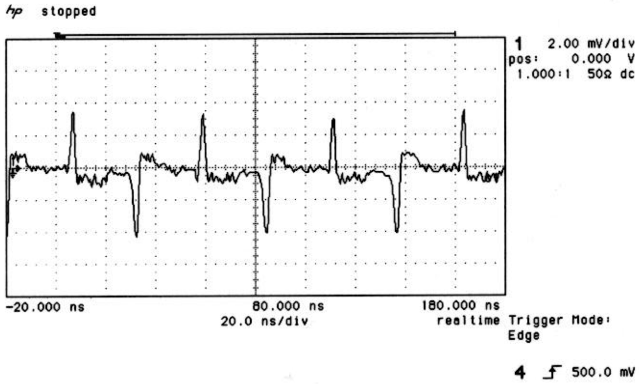

Figure 6. E-Field Probe Above Loop

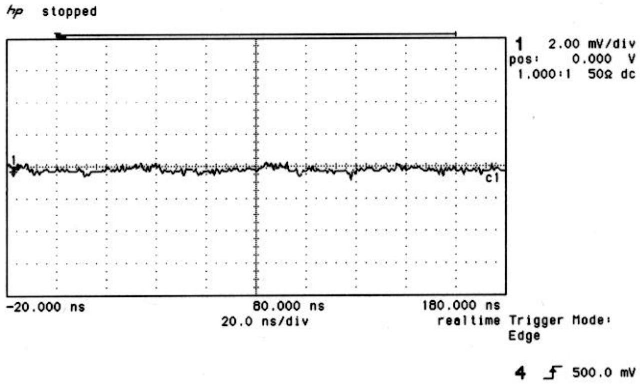

Figure 7. E-Field Probe at Center of Loop

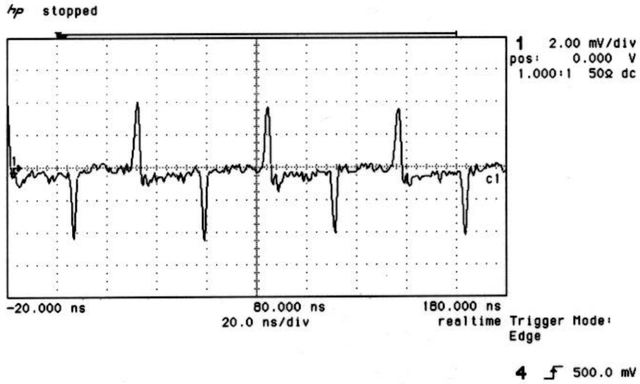

Figure 8. E-Field Probe Below Loop

When the E field source is over the gap, the loop has no output. However, when the electric field source is moved to the sides, the shielded loop has an output due to the unequal shield currents flowing on opposite sides of the loop. The relative phase of the loop output is reversed when the electric field source is moved to the opposite side of the loop.

For many circuit level measurements, an unshielded loop works well. Such a loop can be made out of a paper clip and a BNC barrel adapter. A picture of paper clip loop is shown in Figure 9. There are several ways to test for interference from electric fields. These will be discussed with each application below.

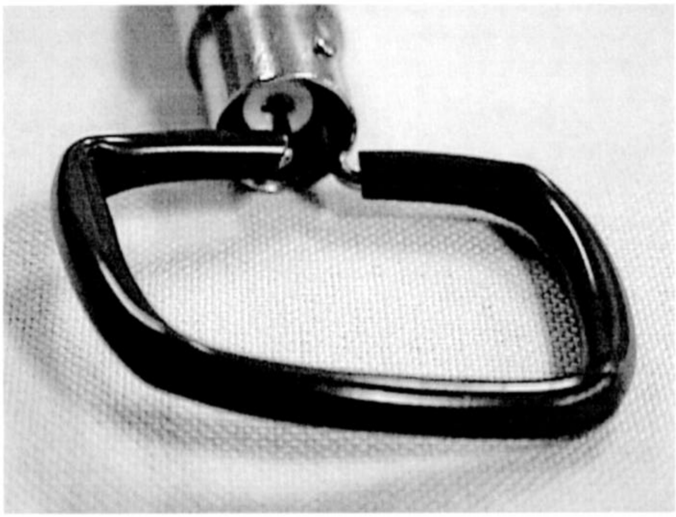

Figure 9. A Simple Unshielded Paper Clip Loop

Unshielded loops have the advantage that the loop can be positioned closer to the circuit being measured. This results in higher sensitivity. The insulation should be as thin as possible to accomplish this. For shielded loops, the diameter of the shielded cable should be as small as possible.

Loop Applications

With the loop operation behind us, let's delve into a few applications of magnetic loops at the circuit level. There are many useful circuit level tests that a magnetic loop can do. We will look into only a few of many possibilities here.

Estimating Crosstalk on a Printed Wiring Board

An unshielded loop works well for estimating the crosstalk due to magnetic coupling into a path on a printed wiring board from nearby parallel paths. The path of interest must be accessible, on the outer layers of a multilayer board or on a two layer board.

Place the unshielded loop over the conductor of interest and connect it to an oscilloscope, terminating the coax cable with 50Ω. If the loop is close enough to the printed path of interest it will pick up crosstalk from nearby paths. If a one cm loop is used and it picks up 80 mV of noise, then the path of interest probably is picking up a similar signal. If the crosstalk coupling length was 10 cm long, there could be 800 mV peak of crosstalk on the board, too much for reliable operation.

A quick check for interference from stray fields or capacitive coupling is to turn the loop 90^o with respect to the parallel paths. If the coupling is from magnetic fields, the loop output should experience a sharp null at a 90^o orientation to the parallel paths. Another quick test is to reverse the loop 180^o. The display on the scope should now be inverted if it is due to magnetic coupling.

Measuring Voltage Drop Across Conductors

Since the loop output voltage is a lower bound estimate of the inductive voltage drop across the conductor the loop is positioned against, a pickup loop can be used to measure the total voltage drop across the conductor (for small portions of a wavelength). This method has been applied to estimating the voltage drop across the bonding wires of a chip in its package with good success.[3]

Voltage drops across ground or power paths on two layer printed wiring boards can be easily estimated using this method. In most cases, just multiply the loop output by the number of loop lengths that the path is long. This gives a reading that is about 1/4 to 1/2 of the actual voltage drop across the path.

As before, by rotating the loop one can check to see if there is any interference from stray fields or capacitive coupling.

Tracking Currents on a Conducting Plane

Another use is to track currents on a conducting plane or structural members of an enclosure. The output of the loop will have a broad peak when the loop (square works best) is parallel to the current. A sharp null will be observed when the loop is perpendicular to the current flow.

A rough estimate of the transfer impedance for a 2.5 cm square loop very close to the conducting plane and in the flat region of frequency response, about 100 MHz to 1 GHz, is about 6Ω. This assumes that the current is concentrated under the loop. The calculation is similar to calculating the transfer impedance of a current probe.[4]

Measuring Induction into Conductors

Often, a local magnetic field itself cannot radiate at lower frequencies, especially below 100 MHz. However, if that field intersects a cable, enough voltage can be induced in the cable to drive it as an antenna. The result can be significant radiation from the cable that can cause compliance problems.

The extent of a possible problem of this type can be estimated using a magnetic loop. Suppose that a cable presents an impedance of 75Ω to the induced voltage of a local magnetic field, a reasonable impedance for a $\lambda/2$ dipole. Computations and experience show that a $\lambda/2$ dipole carrying 15 μamps or more of common mode current can radiate enough to become a compliance issue.

Only about 1.1 mV can drive 15 μamps into 75Ω! If a magnetic loop of 2.5 cm or so picks up this much voltage when held in a local magnetic field, say on a printed wiring board, so can any cable. It is likely a cable that happens to become positioned in the same area will also pick up that much voltage, possibly more if the local field is larger than the size of the loop. In this way, a magnetic loop can be used to evaluate potential problems due to local magnetic fields.

Using the Relative Phase Between Two Loops

The relative phase between two loops can be used to locate a source of noise in a circuit. Figure 10 shows a grid of conductors with a noise source in one branch.[1] By using the phase information between two loops, the branch with the source is easily found.

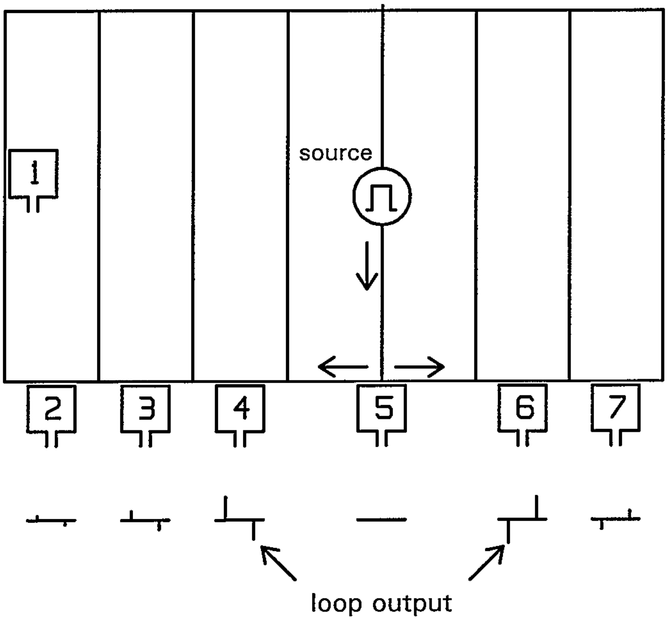

Figure 10. Finding a Noise Source

The essence of the method is to use one loop to pick up the noise whose source is to be found and that signal provides a stable trigger for an oscilloscope. A second loop is then moved around the circuit and variations in it's output relative to the first loop locates the noise source.

In Figure 10, the first loop is held at position 1. In reality, the stable scope trigger could just as easily be furnished by a standard scope probe as well as a loop. In this example a second loop is then moved along the bottom of the grid from left to right. The resulting scope patterns are shown below the respective positions, 2 through 7.

If the noise source is a pulse, then the loops will pick up the L•di/dt edges of the pulse plus any ringing and other signals in the circuit. Let's concentrate on just the L•di/dt edges. At position 2, the movable loop shows small L•di/dt edges. At position 3, the contribution of current from another branch results in higher loop output. At position 4, the loop output amplitude continues to increase as the next branch is passed. Since the current from the branch containing the noise source splits at position 5, the loop output goes though a null as the loop passes position 5. This is because the current flowing to the left generates an opposite voltage in the loop as the current flowing to the right.

After position 5 is passed, the current is now flowing from left to right instead of right to left and the loop output is reversed in polarity as shown in Figure 10. As the loop continues to move away from the source and additional branches siphon off current, the loop output decreases.

The null and phase reversal are critical. They indicate the location of the noise source branch.

Noise Injection

A magnetic loop can also be used to inject noise into a circuit. The injected noise is in series with the chosen conductor, a feat difficult to achieve, normally requiring breaking the path to insert the noise.

A small loop, about 2.5 cm is reasonable, is connected to an IEC 1000-4-4 Electrical Fast Transient (EFT) Burst generator. My experience is that 10 volts of noise can be injected per 1000 volts of generator setting into a cable or a path on a two layer printed wiring board, less into a path on a multilayer board. Since the noise burst from the generator consists of hundreds and thousands of pulses, there is ample opportunity for the noise to cause problems in circuits. The noise pulses induced in the circuit have risetimes of about 5 ns and widths of approximately 10 ns.

One use of this method is to measure noise margins in circuits. A scope probe is connected to the input of the device whose noise margin is to be measured. Then the noise is injected and its amplitude is slowly increased over a minute or two. The noise amplitude is increased slowly to allow ample opportunity for one of the thousands of EFT pulses to coincide with noise and signals in the circuit. The amount of noise that causes a problem is the noise margin of the circuit.

The practical limit on the amount of noise that can be injected is about 15 to 20 volts. Above that, the BNC hardware typically used with magnetic loops begins to spark over. I use an insulated paper clip loop so as not to damage an expensive shielded loop.

MULTIPLE TURN LOOPS

Finally, what happens if the loop has multiple turns? Faraday's Law states that the *open* circuit voltage should double making the loop more sensitive. However, with the effect of the 50Ω termination usually present on a loop, the picture changes dramatically. Figure 11 illustrates this.

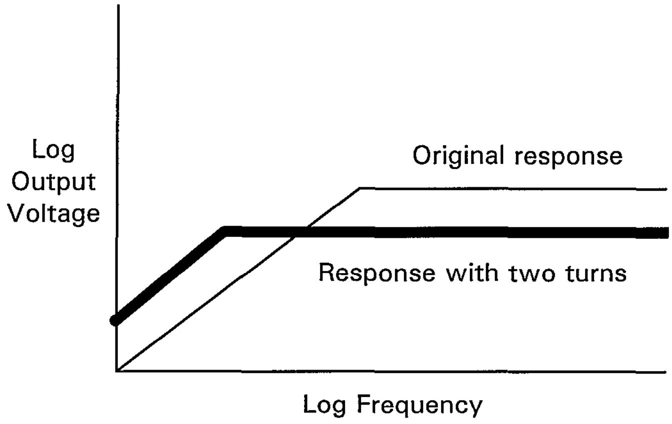

Figure 11. Response of Loops With One and Two Turns

The open circuit voltage does indeed approximately double (sloped part of the curve). However, the inductance increases (for tightly coupled turns) as the square of the number of turns and so increases by a factor of 4. This reduces the corner frequency of the inductance and the 50Ω load to one fourth of the frequency.

The result is that a two turn loop is about 6 dB more sensitive at low frequencies and 6 dB *less* sensitive at high frequencies to a current flowing in a conductor. Interesting.

CONCLUSIONS AND SUMMARY

Magnetic pickup loops, both shielded and unshielded, square and round, can be used to measure and troubleshoot circuits and designs. Methods of using such loops have been presented that extend the usefulness of these loops beyond the normal EMC use of measuring magnetic fields.

REFERENCES

1. Figure from the manuscript of *Troubleshooting Electronic Circuits and Designs Using High Frequency Measurements*, Douglas C. Smith, work in progress. Used with permission.

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