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ABSTRACT - EMI test procedures specify that long cables should be bundled at their center in some circumstances. Although it is clear that this practice can have a significant effect on the measured EMI, this effect is complex and difficult to predict. This paper investigates the effect of cable bundling using analytical models and measurements. It also looks at how cable bundle parameters such as length and "tightness" can affect the repeatability of the measurement.

INTRODUCTION - The length and position of the interconnecting cables are often among the most significant parameters affecting the level of conducted or radiated electromagnetic interference (EMI) from a system. Early EMI test procedures did not specifically address the disposition of the cables other than to state that emissions should be maximized. As a result, different EMI test labs would come up with very different "worst case" test configurations for the same system.

In an attempt to make EMI testing more repeatable, recent EMI test procedures have been more specific about cable length and placement. The FCC EMI test procedures [1,2] state that long cables should be bundled under some circumstances. Cable bundles are to be "30 to 40 cm" in length and located near the center of the cable. Other parameters of the bundle such as the number of "loops", tightness, or shape are not specifically addressed, although the procedures do state that cables are to be bundled in a "serpentine fashion".

The practice of bundling cables when making EMI measurements raises two important questions:

1. What effect does bundling the cable typically have on a measurement?

2. How critical are the various bundle parameters (e.g. length, shape) to the repeatability of the measurement?

A simple model of a table-top EMI source with a bundled cable can be used to illustrate the effect that various cable parameters potentially have on the radiated fields. Although the model and measurements presented here do not account for all possible cable bundle/EMI interactions, they illustrate the magnitude of the EMI measurement repeatability problem and demonstrate the relative importance of various cable bundle parameters.

LUMPED-ELEMENT MODEL - Consider the simple model of a table-top source illustrated in Figure 1. The radiation from table-top sources at

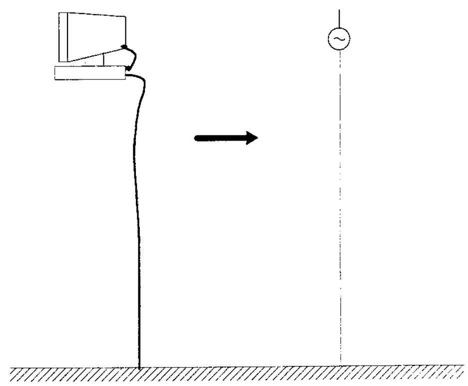

Figure 1: Simple EMI Source Model

frequencies below 100 MHz is often dominated by the currents induced on the power and interface cables [3]. A simple model consisting of a cable driven near one end by an unknown source is very helpful for analyzing how various changes in the cable length, termination, and position affect the induced currents and radiated fields [4]. A typical plot of the cable current as a function of frequency is shown in Figure 2. Note that peak currents occur at frequencies where the "system" is resonant. For a straight wire shorted to the ground plane, these

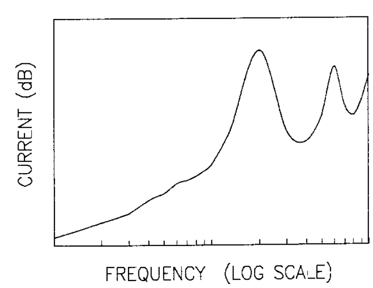

Figure 2: Typical Plot of Induced Cable Currents

resonant frequencies occur at frequencies where the length of the wire is approximately a quarter-wavelength.

Now consider the model of a table-top source with a bundled cable illustrated in Figure 3. The impedance of the cable bundle is represented as a lumped element. The resistance and radiation loss

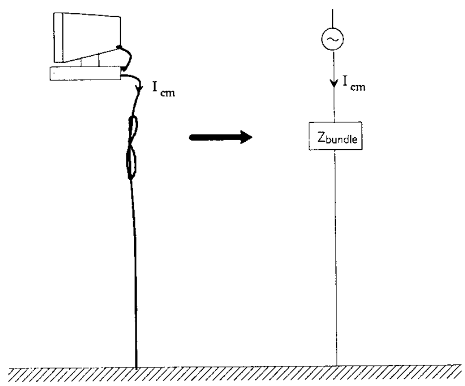

Figure 3: Simple EMI Model with Bundled Cable

are neglected in this model causing the impedance to be a pure reactance. To obtain a simple, first-order approximation for what the value of this reactance should be, the cable bundle can be modeled as a series of shorted transmission lines as shown in Figure 4a. or a series of open and shorted transmission lines as shown in Figure 4b. The choice of models depends on the orientation of the cable bundle. For a cable oriented as shown in Figure 4a., the input impedance of each transmission line is given by,

$$Z_{in} = j Z_o \tan \beta l \qquad (1)$$

$$\text{where: } Z_o = \frac{1}{\pi}\sqrt{\frac{\mu}{\varepsilon}} \cosh^{-1} \frac{s}{d}$$

s = *center–to–center cable separation*
d = *cable diameter*
β = *phase constant*

The permittivity and permeability of free space can be used for ε and μ in this model although slightly different values (depending on the cable insulation properties) may be more appropriate for a tightly bundled cable. An approximate expression for the overall lumped impedance of a cable bundled with N loops is,

$$Z_{bundle} = j N^{\alpha} \frac{1}{\pi} \sqrt{\frac{\mu}{\varepsilon}} \cosh^{-1} \frac{s}{d} \tan \beta l \qquad (2)$$

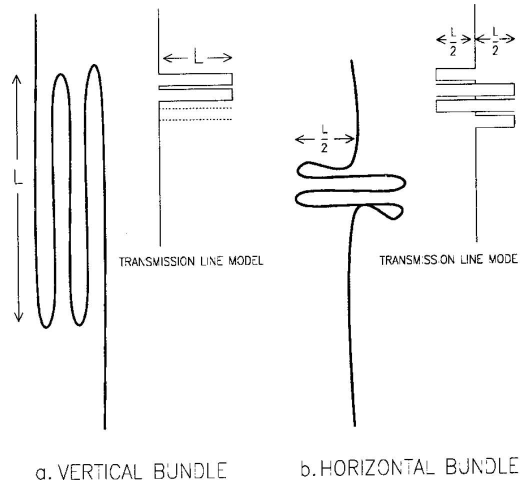

Figure 4: Transmission Line Models

where the value of α depends on the relative amount of coupling between the "loops". Flat cable bundles with relatively insignificant inter-loop coupling would have a value of α near 1, while cables that are more tightly bundled may have a value of α approaching 2.

Note that the expression for the impedance of the cable bundle contains a term that depends on the inverse hyperbolic cosine of the ratio of the cable separation, s, to the cable diameter, d. A plot of the inverse hyperbolic cosine function is shown in Figure 5. Note that when $s \approx d$ (i.e. the cable is bundled tightly) the value of this term is very sensitive to small perturbations in s. In other words, we might expect the impedance of a tightly bundled cable to vary significantly from the impedance of a "not so tightly" bundled cable.

The length of the bundle is another parameter that contributes to the overall impedance. At low frequencies, the $\tan \beta l$ term in Equation 2 is roughly proportional to the length, l (since $\tan \beta l \approx \beta l$ for small values of βl). However, at frequencies where the length of the bundle is an integer multiple of a quarter-wavelength, small changes in the length have a big impact on the bundle impedance.

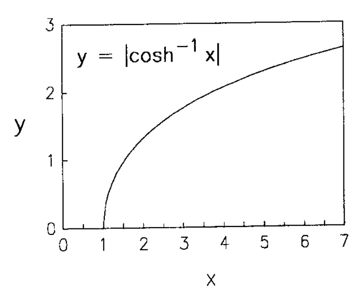

Figure 5: Inverse Hyperbolic Cosine Function

Referring back to the radiation model of Figure 3, a question that remains is "How much change is required in the cable bundle impedance to significantly affect the common-mode cable current and therefore the measured EMI"? The answer to this question depends on the relationship between the cable bundle impedance and the "wire impedance" [3], where wire impedance is defined as the ratio of the open-circuit voltage to the common-mode current at a point on the radiating wire

When the wire impedance is relatively high at the cable bundle location, the bundle impedance does not have a big effect on the net cable current. At frequencies where the wire impedance is relatively low (e.g. near resonance) the net current is inversely proportional to the cable bundle impedance. At these frequencies, significant changes in the cable bundle impedance translate to significant changes in the radiated fields.

At frequencies where the reactance of the wire is approximately equal in magnitude and opposite in sign to the cable bundle reactance, the presence of the cable bundle creates a resonant condition. In this situation, cable currents are maximized and small changes in the cable bundle impedance can have a big effect on the cable current.

Another way of viewing this situation is to observe that, in general, the presence of a cable bundle shifts the resonant frequencies of the system. The cable bundle impedance is a critical factor at frequencies near these resonances and it is a relatively unimportant factor away from resonance. Unfortunately, the highest current and the maximum radiation generally occur at frequencies near resonance. As a result, cable bundle parameters tend to have the greatest impact at the frequencies of most concern to the EMI test engineer.

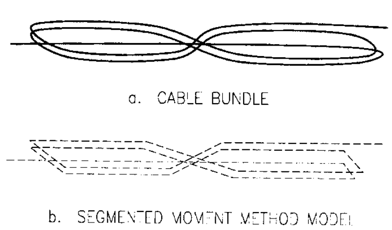

Figure 6: Moment Method Cable Bundle Model

MOMENT-METHOD MODELING - The model of the previous section is useful for illustrating the relative effects of certain cable bundle parameters, but it is much too simple to be used to model the behavior of a realistic EMI source configuration.

On the other hand, numerical electromagnetic analysis techniques based on the method-of-moments can be used to model a variety of EMI problems [4-6]. These techniques are particularly effective for analyzing configurations where the EMI is dominated by the cable currents.

Tightly bundled cables cannot be modeled using general purpose moment-method codes, because the wire separation is generally constrained to be several times the wire diameter. However, a configuration similar to the one illustrated in Figure 6 (representing a loosely bundled cable) is readily

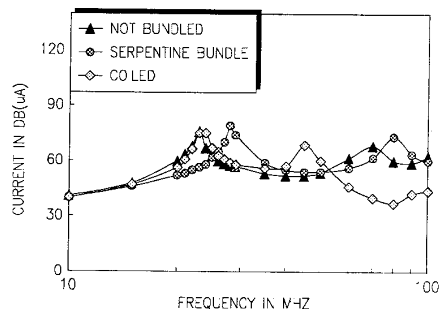

Figure 7: Moment Method Analysis Results

analyzed. A moment-method analysis of this configuration is useful because, unlike the lumped element model, it correctly accounts for the inter-loop coupling and the loss due to cable resistance and radiation.

Figure 7 shows the result of a moment-method analysis of a cable configuration similar to the one shown in Figure 6. The common-mode current is plotted as a function of frequency with the bundle absent, with a "serpentine" bundle, and with a coiled bundle. The dimensions of the bundle were constant so the difference in the "serpentine" and "coiled" results is due to the different amount of inter-loop coupling. Note that the most significant changes in the cable current are due to shifts in the system resonance.

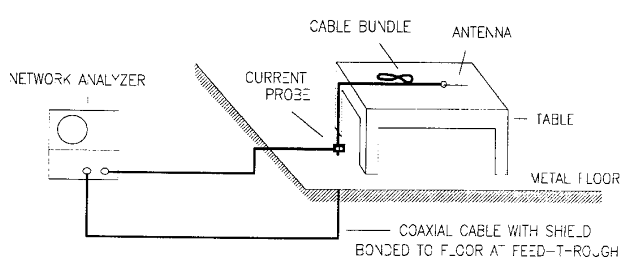

Figure 8: Test Set-Up for Measurements

MEASUREMENTS - The models described above help to illustrate how each cable bundle parameter affects the overall system response. However, the overall effect of the cable bundle on measurement repeatability is best illustrated by making a number of measurements under controlled conditions.

The configuration shown in Figure 8 was constructed in a laboratory. A test cable with a source at one end and a connection to the ground plane at the other end was used because this configuration:

1. presented a relatively uniform common-mode current to the cable bundle
2. could be measured accurately and repeatably
3. lent itself to analysis using a moment-method technique

The common-mode current as a function of frequency was measured for a variety of cable bundle configurations. The source was a 15 cm wire antenna driven by a remote network analyzer. The signal from the analyzer was carried to the source location through the inside of the test cable, which was coaxial. The position of the antenna (e.g. horizontal or vertical) was shown to have no measurable effect on any of the results presented here.

The plot in Figure 9 shows the current induced on the unbundled cable, as well as the current induced with a cable bundle in each of two different locations. The two cable bundles were virtually identical in length and shape, however the first was located 30 cm from the source while the second was located 50 cm from the source. Note that while the bundled cable measurements were significantly different from the unbundled measurements, the actual location of the cable bundle was relatively

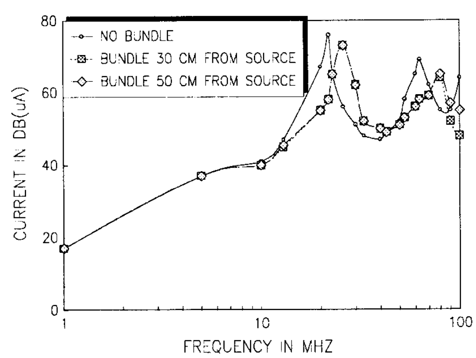

Figure 9: Effect of Changing Bundle Location

unimportant below 90 MHz. This result could be predicted from the lumped element model since, at these frequencies, the wire impedance is nearly constant 30 cm and 50 cm from the source. Since the bundle impedance was not changed, the current induced on the cable was also constant.

At low frequencies the wire impedance is primarily a negative reactance or capacitance [3]. The bundle impedance (Equation 2) is a positive reactance or inductance at low frequencies. The first system resonance occurs at the lowest frequency where these reactances cancel. Therefore, higher cable bundle impedances result in lower resonance frequencies.

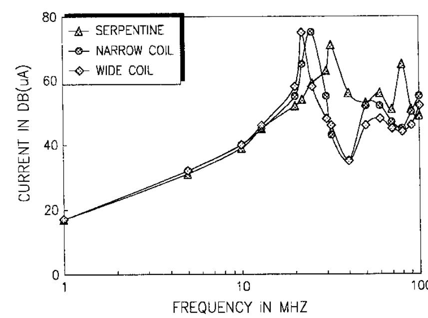

Figure 10: Serpentine Bundle vs. Coiled Bundle

This effect is illustrated in Figure 10. A cable bundled in a serpentine fashion has a smaller impedance at low frequencies than a coiled cable due to its relatively low inter-loop coupling (the parameter α in Equation 2). A coiled cable has a higher impedance (inductance) and this impedance is roughly proportional to the loop area. As the plot in Figure 10 indicates, the configurations with the coiled cable resonate at lower frequencies than the serpentine configuration. The coil with the most loop area produces the lowest system resonance.

Note that the second resonance that occurs with the serpentine configuration is not simply shifted by the same amount as the first resonance. This is because the wire impedance and the bundle impedance do not vary with frequency in the same manner. Even for the simple configuration measured here, the effect of bundle parameter changes at higher frequencies is very difficult to predict.

Figure 10 illustrates how a significant change in the cable bundle can affect the cable currents. A question that remains is "How much repeatability can be expected when the cable is bundled in the same location, with the same length, and the same number of turns by two different test engineers?" The plot in Figure 11 shows the current induced on a cable with each of two nearly identical single-loop cable bundles. First, the cable was loosely bundled in a manner similar to the illustration in the FCC test procedures [1,2]. The configuration was measured and then remeasured after "tightening up" the cable bundle so that there was less space between wires. As the plot in Figure 11 indicates, at most frequencies there was very little change in the induced currents. However, at frequencies near resonance (where most EMI problems related to the cable

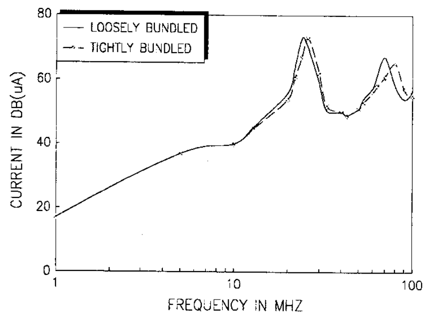

Figure 11: Effect of Bundle "Tightness"

would occur), the magnitude of the change was as high as 10 dB. This illustrates how even seemingly insignificant changes in cable bundling technique can significantly affect an EMI measurement.

CONCLUSIONS - Simple models of a bundled cable suggest that relatively small changes in the geometry of the bundle, can significantly affect the common-mode cable current. Parameters such as length, tightness, location and the number of turns determine the impedance of the bundle. As the impedance of the cable bundle changes, the resonant frequency of the system shifts. This can result in large changes at the very frequencies where EMI problems are most likely to occur.

Two different test labs measuring the same system can get significantly different results due to minor differences in the way the cables are bundled. Therefore, it is a good idea to test each system with a few different cable bundle configurations in order to determine if there is a potential repeatability problem.

Lossy cables or cables with a lossy common-mode termination are less-likely to be sensitive to minor changes in cable bundle parameters. The resonant peaks in a lossy system are smaller and cover a wider band of frequencies. Small shifts in the resonant frequency do not have as much of an impact on the currents induced at any one frequency. Unfortunately, very few systems have sufficiently lossy cables or terminations and the FCC test procedures do not allow artificial lossy cable terminations (such as the CISPR clamp) to be used for EMI testing. However, measurements of the current on each cable using a lossy termination can be a useful supplement to the other data collected during an EMI test. This data is less sensitive to details of the test set-up and provides a better indication of how likely it is that a particular system could become a significant source of EMI.

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