Validation of Worst-Case and Statistical Models for an Automotive EMC Expert System

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Abstract—**Previous papers have presented algorithms for an EMC expert system used to predict potential electromagnetic compatibility problems in a vehicle early in the design process. Here, the accuracy of inductive and capacitive coupling algorithms are verified through representative measurements of crosstalk within an automobile. Worst-case estimates used by the algorithms are compared to measured values and are compared to values estimated using statistical methods. The worst-case algorithms performed well up to 10-20 MHz, but overestimated measured results by several dB in some cases and up to 10-15 dB in others. An approximate statistical variation of the current expert system algorithms also worked well and can help avoid overestimation of problems; however, worst-case estimates better ensure that problems will not be missed, especially in the absence of complete system information.**

Keywords: **Approximation methods, crosstalk, modeling, vehicles, harness wiring.**

I. INTRODUCTION

Designing automobiles for electromagnetic compatibility (EMC) is increasingly challenging. Automotive engineers face significant pressure to develop systems quickly and at low cost. At the same time, the number and complexity of both wired and wireless electronic devices is growing rapidly, so much so that the value of electronics in high-end vehicles promises to overtake the value of mechanical components in the near future. Predicting potential electromagnetic compatibility issues early in the design process is critical to meeting these challenges. Problems that are not found until a prototype is produced can be very expensive to fix or may not be fixed at all. Analyzing the entire system with a complex analysis tool – for example, full-wave modeling of the electronic components, sheet metal, and harness wiring – is usually infeasible. It is difficult to obtain all the information needed to perform such analyses – for example, to obtain complete geometry. The complexity of the system requires an overwhelming amount of time to compute a single result much less to handle many parameter variations, and results are difficult to understand because the impact of a single parameter or module often can not be isolated from the entire system.

To help solve these issues, an automotive EMC expert system is being developed to better identify EMC problems early in the design of an automobile [1]. The goal of the system is to rapidly analyze a design for a wide variety of EMC issues, determine potential EMC problems, and point the user toward potential solutions. Because the expert system must be run early in the design, it is being developed to run with incomplete system information. To allow for rapid analysis, the expert system relies on rules of thumb and approximations. The approximations allow many design alternatives to be explored quickly and allow a clear link between specific problems and their solutions. While the expert system results will not give precise levels of emissions or crosstalk, they will reveal specific problem areas and allow the user to focus their attention on these problems. Once a potential problem is identified, the user can perform a more sophisticated, but time consuming, numerical analysis if they feel it is required to fully assess the problem.

Current expert system algorithms for crosstalk use simple lumped-pi approximations for inductance and capacitance [1], similar to approximations proposed by others [2]. These lumped element approximations are appropriate at the frequencies of interest – up to tens of MHz – for the size circuits under consideration. The algorithms assume worst-case conditions. For example, that two wires in a harness sit next to one another for the entire length of the harness. The risk of using worst-case assumptions is that crosstalk will be overestimated and problems will be identified that are not realistic – at least not realistic for a large percentage of vehicles. Previous experiments with cable harnesses have shown the coupling may vary by more than 20 dB depending on relative placement of wires in the harness [3][4]. Variations in distance from the current return path, load, and other parameters should also be considered.

Several statistical methods for analyzing crosstalk in a harness have been proposed. The work by Paul et al. [3][4] experimentally examined the statistical variation of crosstalk as a function of wire position in the cable harness. Later work showed these results could be reproduced through simulation using a segmented multiconductor transmission line model, where wire position is varied from one segment to another and many configurations are explored using Monte Carlo methods [5]. Statistical variation can be determined faster and more accurately using methods that smoothly vary the wire path through the harness and that predict crosstalk from untried parameter configurations using interpolation techniques [6]. Such statistical methods have also been extended to predict common-mode radiation from cable harness bundles [7]. While these methods may be too computationally expensive for an expert system, closed form expressions for the statistical variation of coupling within a harness have also been developed [8] that may adequately meet the requirements of an expert system for rapid calculation of results and for a clear link between problems and their cause.

The goal of the following paper is both to validate current expert system algorithms, which rely on worst-case estimates of crosstalk, and to compare these results with a statistical approximation of crosstalk in the vehicle. Current algorithms are validated through comparison to measurements of crosstalk taken on the wiring harness of an automobile. Comparison of worst-case and measured results is followed by a comparison to statistical results that are estimated using Monte Carlo methods.

II. Validation of Crosstalk Algorithms

Crosstalk was measured for a variety of configurations both between circuits sharing a harness in the engine compartment and for circuits sharing a harness in the passenger compartment. Measurements and calculations were performed using both real and imposed values of impedance for the modules that were part of the circuits. Imposed values of impedance were used so that a greater variety of conditions could be measured, for example to ensure that either capacitive or inductive coupling dominated. Actual module impedances were found using a network analyzer by measuring S_{11} looking into the module. Crosstalk measurements were performed for a wide variety of configurations, including crosstalk between:

- Two circuits, both with their own return wire;
- Two circuits sharing the same return wire;
- Two circuits using body-surface metal as return;
- One circuit using a return wire as return, one circuit using body-surface metal as return;
- Two circuits using a combination of wire and body-surface metal as return;
- One circuit using a twisted pair, one circuit using an (untwisted) wire return.

For each configuration, measurements were made between multiple wires in the harness to test coupling between circuits at multiple locations in the harness.

Values of crosstalk were measured using a network analyzer by measuring S_{21} looking into the harness. In this case, either the source or load was replaced by the network analyzer. While this technique was not ideal, as we would prefer to use only the true source and loads, it greatly simplified measurements and allowed testing over a much greater frequency range than if the actual source and loads were used. The technique should not significantly alter the results in terms of the range of performance that can be expected from the expert system. In these tests, as in the expert system, it is assumed that the value of crosstalk is unknown but the source and load impedance and the source current or voltage is available, in addition to approximate system geometry.

Measured values of crosstalk were compared to values estimated using an expert system formula. Crosstalk was estimated by the expert system using source and load impedances and the circuit geometry. Values of source and load impedances were taken from the experimental setup and from measured values for the different modules. Possible separations between wires in the harness were estimated from the radii of the wire and harness. Height above the ground plane, where needed, was estimated as a single value. For example, in the engine compartment the average height above the return plane was assumed to be 20 cm and in the passenger compartment to be about 1 cm, though clearly the height will vary along the harness length. Harness length was estimated from available documentation describing the automobile.

A simple first test of the expert system algorithms was to compare the measured self impedance of the circuit to the impedance calculated by the expert system. Fig. 1 shows one example measurement looking through the harness into the power control module when the current returned on one or more wires in the harness. Measurements show the module appears as an approximately 10-nF shunt capacitor and the (external) inductance of the loop formed by the circuit is approximately 2.5 µH. Using the worst-case separation among wires, the expert system would have estimated the inductance of the loop to be 3.1 µH, or an overestimation of about 30%. Similar results were found with other configurations.

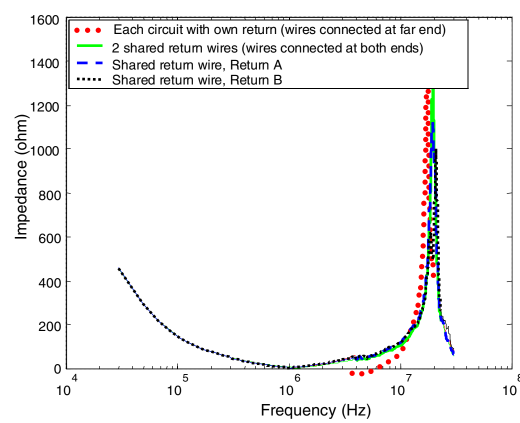

Figure 1. Measured impedance of power control module and harness connections.

Figs 2 and 3 show examples of measured and estimated values of crosstalk in the vehicle, in this case for the circuits measured in Fig. 1. The culprit circuit either used its own return wire or shared return wires with the victim. Expert system estimates were made assuming the worst-case position of wires in the harness. Impedances were such that inductive coupling dominated. The expert system estimates were within about 6-10 dB of the measured values up to around 20 MHz. Above 20 MHz, the expert system model begins to break down, however calculation to 20 MHz is adequate for most applications of this system. Better estimates of crosstalk could be found using more accurate values of self- and mutual inductance, as indicated in Fig. 4 where measured values of inductance are used. However these values are not usually known *a priori*.

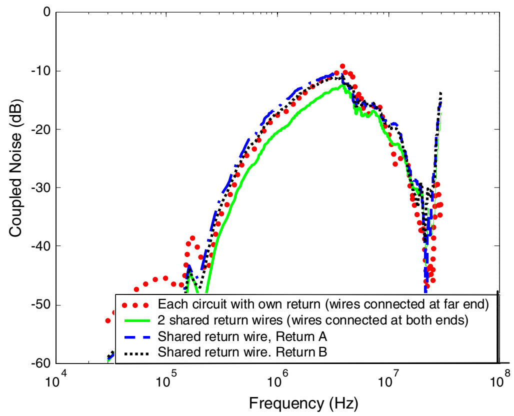

Figure 2. Measured crosstalk among circuits with separate or shared return wires when inductive coupling dominates.

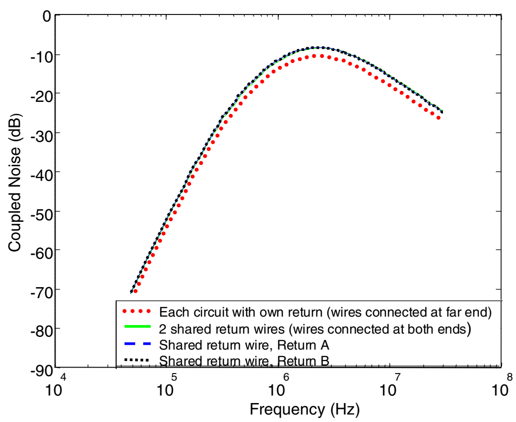

Figure 3. Expert system estimates of crosstalk among circuits with separate or shared return wires when inductive coupling dominates.

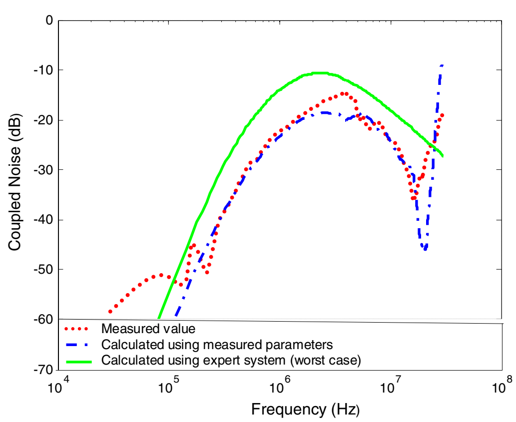

Figure 4. Estimated and measured crosstalk when estimates were calculated using worst-case and measured values of inductance.

An example of capacitive coupling among the wires in Fig. 1 is shown in Fig. 5. In this case, the circuit loads were set to open to guarantee that capacitive coupling dominated. Using worst-case estimates of wire position and permittivity (i.e. using ε_r=2 for the relative permittivity of the intervening wire insulation), coupling was overestimated by about 10-15 dB. The estimate broke down beyond several MHz. Despite the overestimation, worst-case estimates may be appropriate when the wire position is not known. Using best-case estimates would underestimate coupling by about 6 dB. In other measurements, the difference between the measured values and the worst-case estimates was as low as a few dB.

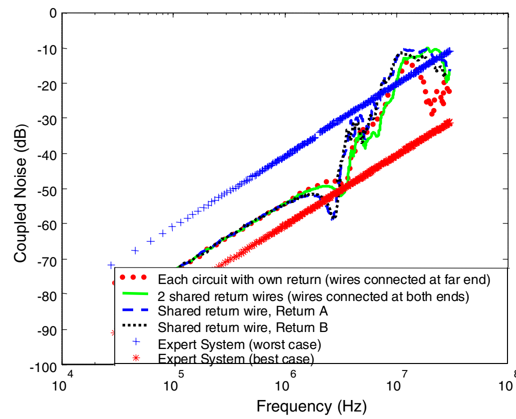

Figure 5. Measured and estimated crosstalk among circuits with separate or shared return wires when capacitive coupling dominates.

Additional examples of measured and estimated crosstalk are shown in Figs 6 and 7. Fig. 6 shows a case where both capacitive and inductive crosstalk are important and where both body surface metal and a wire were used as a return. In this case, a wire was run through the harness for about 1.0 m before connecting to body surface metal. Beyond tens of kHz, currents tend to use the wire as the return for the 1.0 m of the harness where it is available and use the body surface metal for the remaining 0.8 m where it is not. Fig. 7 shows measured and estimated crosstalk to a twisted pair. For twisted pairs, the expert system algorithm assumes coupling only at connectors where wires are untwisted and separated allowing possibly significant coupling to occur [1].

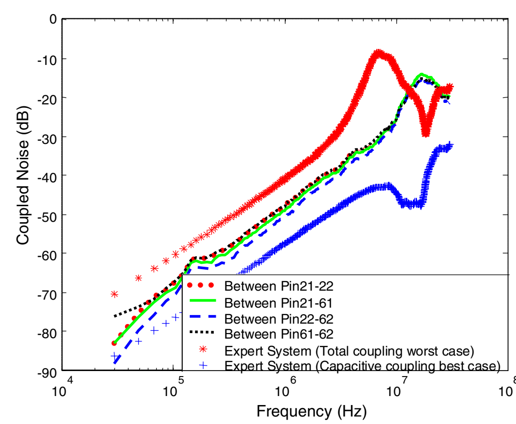

Figure 6. Measured and estimated crosstalk when capacitive and inductive coupling were important and multiple return structures were used.

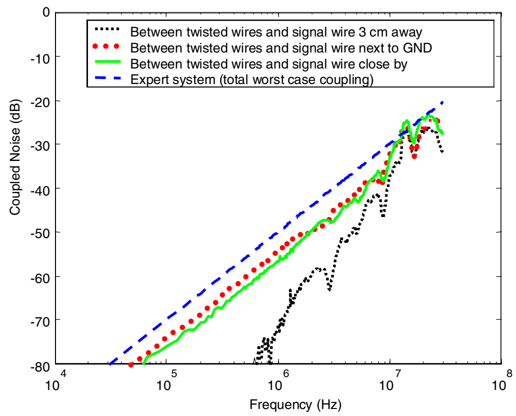

Figure 7. Measured and estimated crosstalk to a twisted pair.

Many other cases were tested than are shown here. In general, the expert system algorithm overestimated coupling since it used worst-case estimates for wire position and medium permittivity. In some experiments, coupling was overestimated by 10-20 dB. In other experiments, however, coupling was overestimated by only a few dB. Estimates were generally good up to several MHz or tens of MHz. The fact that coupling was overestimated by only a few dB in some experiments indicates the strength of using worst-case estimates when system parameters are unknown.

III. STATISTICAL ANALYSIS

The problem with worst case estimates is that the worst case may never actually occur or may only occur in a very few instances. Using worst-case analysis may lead to overdesign or may cause the expert system to report an overly large number of potential problems – requiring the human user to prove or refute the seriousness of those problems. A statistical analysis of crosstalk among circuits may better allow the expert system to exclude cases that would only rarely occur and to report issues that may be a problem in only the "reasonable worst case".

A statistical analysis of crosstalk was performed on many of the same circuits that were analyzed with the worst-case expert system algorithms in the last section. To simplify analysis, statistical estimates of crosstalk were made using Monte Carlo methods, which could be applied with only minor modifications to the current expert system algorithms.

An initial comparison between the worst case and statistical results can be obtained by comparing calculations of mutual inductance or capacitance. One approximate method that might be used to calculate mutual inductance or capacitance is to use average separation distances between wires in the harness and then calculate error bounds by estimating the variance about these average inductance or capacitance values. Assuming the location of a wire is uniformly distributed through a 3-cm diameter harness, Monte Carlo analysis shows that the average distance between 2 wires is about 1.08 cm, or about one-third the harness diameter, and variance is 8.7 mm. For two circuits sharing a common return wire in the same harness, mutual inductance per-unit-length can be approximated as

$$l_m = \frac{\mu_0}{2\pi}\ln\left(\frac{d_G d_R}{d_{GR} r_{w0}}\right)$$

where l_m is the mutual inductance per-unit-length, d_G is the distance between one signal wire and the return, d_R is the distance between the other signal wire and the return, d_{RG} is the distance between the signal wires, and r_{w0} is the radius of the return wire. If the wire is approximately 0.5 mm in diameter, which is common among wires in the harness, then the worst case mutual inductance is approximately 1500 nH/m, the best case mutual inductance is approximately 277 nH/m, and the average mutual inductance (calculated using average distance) is approximately 757 nH/m. The variance of the mutual inductance can be approximated as

$$\sigma = \sqrt{\left[\frac{d(l_m)\sigma_{d_G}}{d(d_G)}\right]^2 + \left[\frac{d(l_m)\sigma_{d_R}}{d(d_R)}\right]^2 + \left[\frac{d(l_m)\sigma_{d_{GR}}}{d(d_{GR})}\right]^2} = 273\,{}^{nH}\!/_{m}\,.$$

Assuming values of mutual inductance can be described with a Gaussian distribution (which is not wholly accurate [8], but is reasonable for this analysis), then 80% of the values of mutual inductance will fall within 1.25 standard deviations from the average, or in this case within the interval l_m = (415 nH/m, 1100 nH/m). Estimating the statistical variation in mutual inductance using Monte Carlo methods for 2000 sample configurations gave an average per-unit-length inductance of 722 nH/m and an 80% confidence interval of (472 nH/m, 972 nH/m). While the approximate calculation based on average distance did not yield the same results as the Monte Carlo simulations, the result is close. Measurements in the vehicle generally yielded values of mutual inductance within this 80% confidence interval.

Similar experiments were performed for mutual capacitance between two signal wires sharing a common return wire in the same harness. Best and worst case estimates of mutual capacitance per-unit-length were 4.8 pF/m and 17.6 pF/m, respectively. Estimates of mutual capacitance found using the average distance between wires produced an average mutual capacitance of 7.3 pF/m and an 80% confidence interval of (4.3 pF/m, 10.6 pF/m). Estimates of mutual capacitance found from Monte Carlo simulations had an average value of 8.1 pF/m and an 80% confidence interval of (4.9 pF/m, 11.4 pF/m). Again, while the approximate calculation did not yield the same result at the Monte Carlo simulation, the results were close enough for use by the expert system.

Values of crosstalk measured among wires in the harness were also compared to values calculated using the worst-case expert system equations and calculated using statistical methods. One example is shown in Fig. 8 for the same configuration that was measured in Fig. 1, where two signal wires share a common return in the harness. Measured values of crosstalk are near to the estimated average crosstalk and within the 80% confidence interval. Below 4 MHz, the worst-case estimate of crosstalk is generally about 3 dB higher than the 80% confidence interval and generally about 6 dB higher than the measured crosstalk. Similar results were observed for other circuits.

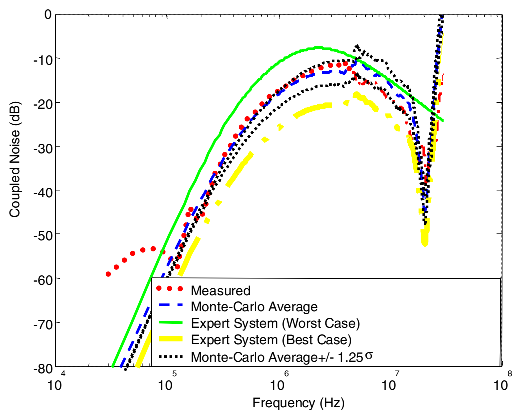

Figure 8. Measured and estimated values of crosstalk found using worst-case and Monte Carlo methods

IV. Conclusions

Worst-case expert system algorithms for crosstalk generally performed well up to several MHz or higher when compared to measurements in the vehicle, though typically overestimated actual values. Crosstalk was overestimated by as little as a few dB to as much as 10-15 dB. Crosstalk is likely overestimated because the true positions of wires rarely (if ever) will occur in the worst-case positions assumed by the expert system. A statistical approach helps to prevent unrealistic overestimation of results. While Monte Carlo analysis is one possible method for applying a statistical approach, preliminary results suggest a simple closed-form solution based on average distances and an approximation for variance may also be used with good results. A similar solution based on probability distribution functions, like those in [8] is also a good possibility and may yield more accurate results.

Statistical methods generally worked well for the cases studied here, however there is still a strong argument for using worst-case analysis. Possible variations in the input data go beyond simple variations in geometry. Circuit terminations may be unknown or incorrectly specified early in the vehicle design. Source currents or voltages in the culprit may similarly be poorly specified. The location of body-surface metal relative to the harness is often not well defined. For example, in one case the harness may be hanging in open air in the engine compartment. In another case, it may be running through a wiring channel with closely spaced metal on all sides. While these parameters will be well known in the ideal case, they may be difficult to determine early in the design process. Rough estimates of parameters such as these are common in the early design stages. Using worst-case estimates helps limit the influence of these unknowns, especially considering the approximate nature of the crosstalk calculations used by the expert system.

References

[1] S. Ranganathan, D.G. Beetner, R. Wiese, T.H. Hubing, "An expert system architecture to detect system-level automotive EMC problems," *2002 IEEE International Symposium on Electromagnetic Compatibility*, vol. 2, pp. 976 – 981, 2002.

[2] W.T. Smith, C.R. Paul, J.S. Savage, S.K.Das, A.D. Cooperider, and R.K. Frazier, "Crosstalk modeling for automotive harnesses," *1994 IEEE International Symposium on Electromagnetic Compatibility*, pp. 447-452, Aug. 1994.

[3] C.R. Paul and G. Capraro, "A probabilistic approach to wire coupling interference prediction," *Proceedings of the 1981 IEEE International Symposium on EMC, Zurich*, 1981

[4] C.R. Paul, "Sensitivity of crosstalk to variations in cable bundles," *Proceedings of the 1987 IEEE International Symposium on EMC, Zurich*, 1987.

[5] A. Ciccolella and F.G. Canavero, "Stochastic prediction of wire coupling interference," *Proceedings of the 1995 IEEE International Symposium on EMC*, pp. 51-56, 1995.

[6] S. Salio, F. Canavero, D. Lecointe, and W. Tabbara, "Crosstalk prediction on wire bundles by Kriging approach," *Proceedings of the 2000 IEEE International Symposium on EMC*, vol. 1., pp. 197-202, Aug. 2000.

[7] S. Sun, J. Drewniak, and D. Pommerenke, "Common-mode radiation resulting from hand-assembled cable bundles on automotive platforms," *Proceedings of the 2006 IEEE International Symposium on EMC,* vol. 2, pp. 298-303, Aug. 2006.

[8] S. Shiran, B. Reiser, and H. Cory, "A probabilistic model for the evaluation of coupling between transmission lines," *IEEE Transactions on Electromagnetic Compatibility*, vol. 35, no. 3, pp. 387-393, 1993.