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Integrating Electromagnetic Compatibility Laboratory Exercises into Undergraduate Electromagnetics

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Abstract

A state-of-the art high-frequency laboratory is being developed for pursuing laboratory exercises in EMC. These exercises are being integrated into three undergraduate electromagnetics courses. Two of the courses are a required introductory sequence. The laboratory exercises are designed to stimulate students interest, motivate them to learn concepts, and provide them with exposure to practical EMC applications. Laboratory exercises are also an integral part of an EMC elective course. This paper describes the laboratory development and discusses experiments that can be integrated into these three courses for teaching fundamental electromagnetics as well as EMC.

1 Introduction

Electromagnetic compatibility (EMC) and interference (EMI) is a critical concern in the design of electronic systems. Stringent government and trade-group regulations are imposed in the US and Europe on radiation from electronic products. Failure to meet these regulations can delay the introduction of a product to the marketplace. Further, electromagnetic emissions from one electronic system can interfere and degrade the performance of other systems. At the printed circuit board (PCB) or electronic subsystem level, noise processes in one circuit can couple to other circuits, resulting in poor performance or malfunctioning. Susceptibility of electronics to external electromagnetic fields is also a driving design consideration in applications including avionics and automotive electronics because reliability of the system is essential. Electromagnetic compatibility difficulties are increasingly being identified as bottlenecks in design cycles. Poorly designed electronics can lead to significant EMC and EMI problems late in the design cycle where retrofits and redesigns become time-consuming and costly.

State-of-the art circuits and systems are operating at high data rates, wide bandwidths, increasingly lower signal levels, and are becoming more compact. In this environment, noise is easily coupled between circuits as well as to and from the external environment through capacitive, inductive and radiated electromagnetic field mechanisms. Emerging high-speed technologies and design trends pose greater challenges for engineers in designing circuits

and systems that operate correctly in a complex and often severe electromagnetic environment, and, which meet strict government and trade-group regulatory standards on emissions, as well as rigorous susceptibility requirements. Engineering students must be cognizant of the effects that distributed parasitic capacitances and inductances will have on circuit and system designs, and must be able to anticipate and diagnose noise problems arising from various electromagnetic field mechanisms.

A project is underway at the University of Missouri-Rolla to develop high-frequency laboratory facilities, and implement laboratory exercises in three undergraduate electromagnetics courses. Many fundamental electromagnetics and EMC principles can be taught through laboratory experiments that require little sophisticated measurement equipment, and successful EMC laboratory manuals have been introduced based on this premise [1]. However, experiments with printed circuit geometries and fast digital technologies require more sophisticated RF test equipment. The fundamental principles in many cases are the same. Yet, while students are eager to work with geometries and situations that look like their computer when they have removed the cover, for example, they take a grim view of experiments that are perceived as contrived. Further, an added benefit is that early and regular exposure to state-of-the-art test equipment helps students overcome inhibitions of working with such equipment in the same manner that few students today are intimidated by computers.

The laboratory facilities are being utilized in three undergraduate electromagnetics courses. Four laboratory exercises are conducted in each of two required introductory courses, and five to eight experiments in a junior/senior level elective in EMC. The objective of the laboratory is to provide a more tangible learning experience for assimilating and understanding fundamental electromagnetics concepts. The laboratory also stimulates student interest, provides case studies of EMC problems [2], and gives students exposure to more sophisticated test equipment.

2 Electromagnetics Education at UMR

The undergraduate electromagnetics curriculum at the University of Missouri-Rolla is typical of many university

programs, including a required two semester sequence of introductory electromagnetics, which can be followed by elective courses in EMC, antennas, microwaves, and high-frequency amplifier design. The undergraduate courses currently offered in the electromagnetics area are:

- 1 EE 271 Fields and Waves I (required)
- 2 EE 273 Fields and Waves II (required)
- 3 EE 355 High Frequency Amplifier Design
- 4 EE 371 Grounding and Shielding (Electromagnetic Compatibility)
- 5 EE 373 Antennas and Propagation
- 6 EE 379 Microwave Engineering

The required two semester introductory course sequence (EE 271 and EE 273) covers the fundamentals of vector calculus, static electric and magnetic fields, Maxwell's equations, time-varying electromagnetic fields, waveguides, and simple radiators. Students typically find these required courses difficult. The material presented is highly mathematical, and many new concepts are introduced. In a strictly lecture course, students at the introductory level often see little relevance of electromagnetic theory to their aspirations as practicing engineers. They therefore have too little motivation other than a desired grade for learning important concepts. The result is a superficial knowledge of the mechanics of problem solving, with little understanding of the underlying physics and practical applications. Introducing students to electromagnetics in a manner that is exciting and demonstrates the relevance of fields principles to their future careers is essential for stimulating interest and motivating students to understand the subject. Laboratory exercises have been introduced to achieve this goal. Studying electromagnetic field concepts in the laboratory through examples of noise problems in high-speed digital design and system interconnection, makes the lecture material seem relevant to the aspirations of students as practicing engineers. In addition, students are exposed to practical experience (albeit limited) in EMC. They are thus able to gain a more intuitive understanding of electromagnetic field concepts, and see the application to many areas of electrical engineering. Since the first introduction of these experiments two years ago, student response has been positive.

A comprehensive course in EMC is essential for practicing engineers in meeting the design challenges associated with high-speed digital technologies. Over the course of the past few years, many universities have been introducing new elective courses in EMC. Approaches taken by other established courses in EMC have appeared in the literature [3], [4]. A junior/senior level elective course in EMC is currently offered every fall semester at UMR (EE 371), and was first implemented in the Fall 1985 semester. The use of EMC examples for illustrating fundamental principles in the introductory courses, as well as the emphasis placed on the practical importance of EMC, has resulted in a steady increase in the number of students in EE 371. Five laboratory experiments were conducted in EE 371 in the previous fall offering, and additional experiments continue to be developed. EMC is a very applied field and hardware oriented, and laboratory exercises have been an important element of the course since its inception. Over the ten year history of the course a set of ten to fifteen basic experiments have been developed, with

students typically performing 5-8 in a semester. New experiments continue to be introduced as well as revamping old experiments as a result of newer laboratory equipment within the past two years.

The project underway implements an undergraduate electromagnetic compatibility laboratory that is used in EE 271, EE 273, and EE 371. The objective of the laboratory is to provide an integrated approach to electromagnetic compatibility and high-frequency design. Engineering education has traditionally followed a "divide and conquer" strategy whereby every subject is relegated to its own course and then reduced and analyzed. Upon completion of the course, students may find it unnecessary to draw upon the information learned for other course work with the exception of more advanced courses in the same subject. An analogous situation is often encountered in industry with electromagnetic compatibility problems. Engineers often design systems with little knowledge of the complex and severe electromagnetic environment in which the system must function. This approach can lead to EMC problems late in the design cycle, requiring costly and time-consuming retrofits to meet specifications and regulatory standards.

The EMC laboratory integrates fundamental electromagnetic concepts and principles into the previous experiences of students through EMC examples, experiments, and demonstrations, and presents electromagnetic compatibility as an integral part of circuit and system design. In the introductory level courses EE 271 and 273, students are introduced to electromagnetics in lecture and the laboratory with examples and laboratory exercises relating to EMC. Students will previously have taken two semesters of circuits, and will also have taken, or be concurrently enrolled in a course in electronic circuits as well as signal analysis. Thus, they will have a knowledge base that allows them to appreciate the relevance of electromagnetic principles to circuit design. After completing the introductory courses, students are able to pursue an elective course for more advanced topics in EMC.

3 Laboratory Experiments

The objectives of the electromagnetic compatibility laboratory development are:

1. to stimulate interest and motivate students at the introductory level to learn fundamental electromagnetics concepts;
2. to provide "hands on" experience with hardware, and case studies for learning abstract concepts; and,
3. to learn fundamental EMC principles and hardware applications in a junior/senior level elective.

3.1 Fields and Waves I

The first semester of the introductory electromagnetics sequence focuses on mathematical methods for fields, and concepts of static fields, including electric fields from charge distributions, voltage, capacitance, the Biot-Savart

law, magnetic vector potential, and inductance. Applications of these concepts in hardware design include developing equivalent circuit models for parasitic coupling through the electric or magnetic field when geometries are small relative to the wavelength. A fundamental knowledge of charge distributions, the electric field, and capacitance, as well as current distributions, the magnetic field, and inductance is required in order to understand parasitic capacitances and inductances, and successfully develop equivalent circuit models. While developing equivalent circuit models is among the most important applications to which students will apply these concepts, it is also among the most difficult for them to assimilate. Equivalent circuit modeling, and the non-ideal behavior of circuits at high-frequencies is stressed in the laboratories of all three courses.

Four experiments are planned for the first semester introductory level electromagnetics course:

1. electrostatic discharge (ESD) phenomena (to be developed);
2. inductance and capacitance in cabling;
3. high-frequency component modeling; and,
4. \vec{E} - and \vec{H} -field probing of noise sources.

Currently three experiments are conducted, and an additional experiment is under development. The new experiment will study electrostatic discharge phenomena, which is an increasingly important consideration in the design of digital systems. Students will employ an ESD simulator to study the behavior of large static electric fields resulting from points and sharp corners on conductors, as well as investigate the path of least impedance followed by the ESD currents. An ESD simulator will be employed with various shaped conductors, and the breakdown distance for a given voltage measured for different shaped conducting objects. Dielectrics will be introduced to demonstrate the difference in breakdown phenomena for dielectrics versus air. Seams will be introduced in the dielectrics to show that discharge currents follow the path of least impedance.

Students also investigate inductance and capacitance in cabling. Among the most important concepts learned in the first semester introductory sequence are capacitance and inductance, and identifying parasitic capacitance and inductance in digital designs requires a sound knowledge of electric and magnetic field behavior, respectively. Students experiment with triaxial and twisted shielded pair cables, and measure the capacitance and inductance between signal lines as well as between signal lines and shields, and determine the mutual capacitances from these measurements.

In the third experiment students study the non-ideal high-frequency behavior of components by measuring and modeling a simple commercial magnetic field probe from 1 – 100 MHz. The probe consists of several turns of wire on a core that is encased in a six inch metal probe shaft with a BNC connector at the output. This probe results in a simple parallel LC circuit, with a finite resistance in series with the L. Students measure the frequency behavior of the probe with a vector impedance meter, as well as the resistance at 1 kHz with an LCR meter. From the

measurements, an equivalent circuit model is developed complete with the element values. Measurements are then compared to the model over a significant frequency range.

The fourth experiment conducted is \vec{E} - and \vec{H} -field probing of noise sources. Students employ commercial probes for studying \vec{E} - and \vec{H} -fields near power supplies, power cables, signal cables as a function of loading, and from digital automotive circuits.

3.2 Fields and Waves II

The second semester introductory level course in electromagnetics focuses on dynamic fields and includes Faraday's law, plane waves, transmission lines, waveguides, and simple radiators. The important concepts for hardware design that are stressed in the laboratory are coupling through the time-varying magnetic field (mutual inductance), equivalent circuit modeling, non-ideal behavior of lumped elements, distributed field behavior, and radiation from digital hardware. The four experiments conducted in the second semester introductory electromagnetics course are:

1. Faraday's law, loops, and inductance;
2. high-frequency component modeling;
3. cross-talk in cabling; and,
4. radiation concepts for EMI from printed circuit board designs.

Students study Faraday's law with mutual inductive coupling between loops as a function of loop areas, distance between the loops, and orientation. Thinking in terms of current paths is also stressed. The consequences for printed circuit geometries and transient signals are also investigated experimentally. Self inductance of circuit loops is also studied in the same experiment with vector impedance measurements. The student hand-out for this experiment is given in the Appendix as an example.

Students also study the non-ideal behavior of circuit elements at high frequencies, and the parasitic inductances and capacitances that result in this non-ideal behavior. Currently, a somewhat contrived situation with a 2.11 mH inductor in series with looped cabling (to provide additional series inductance) to give a two-pole, one zero frequency response in the range 1 – 100 MHz is measured and modeled. The current experiment is in the process of being revamped as a result of new equipment acquisitions. Printed circuit board geometries with multiple poles and zeros will be studied experimentally and modeled. The geometry will be the DC power bus on a multilayered printed circuit board. Students will measure the frequency response of the power bus with a newly acquired vector network analyzer, and determine the power bus interplane capacitance, and interconnect via inductance for surface-mount decoupling capacitors. They will model the power bus using Touchstone and PSPICE, and compare the measurements and models.

Cross-talk in cabling is studied in the third experiment. Mutual inductive and mutual capacitive coupling mechanisms are investigated and the consequences for digital signal coupling are demonstrated. The effects of source

and load impedance are also studied, as well as shielding strategies for minimizing each coupling mechanism. The experimental apparatus is deliberately large, approximately 2 m in length with a 4" planar ground and two signal conductors spaced 1" apart and 3" above the ground. This allows students the opportunity to employ electric and magnetic field probes to compare the relative sizes of the two fields for each coupling mechanism as a function of source and load impedances.

Finally, radiation from geometries characteristic of printed circuits is investigated. Radiation from unintended dipole-like antennas characteristic of EMI antennas on printed circuit boards with attached cables is investigated. A network analyzer is employed as the source and used to measure the common-mode current on a cable. Students apply these concepts in measuring and understanding the common-mode current on an attached cable and resulting common-mode radiation from production automotive hardware. The current laboratory is being revamped to study, in addition, the radiation efficiency as a function of source location along the antenna length, and parasitic source coupling to EMI antennas. Loading and filtering strategies for reducing the common-mode current on EMI antennas will also be studied.

3.3 Electromagnetic Compatibility

The objective of the electromagnetic compatibility course is to improve the ability of the student to anticipate, diagnose, and solve noise problems in electronic circuits and systems by applying fundamental electromagnetic-field principles. Basic electromagnetic concepts are reviewed including Faraday's and Ampere's laws, inductance, capacitance, and radiation, and applications of these phenomena to electronic system design. The non-ideal behavior of devices at RF frequencies is studied, and device models for ICs, capacitors, ferrites and transformers are discussed. Basic EMC principles leading to electronic systems that are electromagnetically compatible with their environment are studied, including crosstalk, grounding, filtering, and decoupling. Students also study ESD, lightning, radiated and conducted emissions, shielding effectiveness, shielding strategies, and reciprocity in EMC. Five experiments were conducted in the previous Fall 1994 offering of this course, and new experiments are under development. Current and planned experiments include:

1. determining the lowest impedance/inductance path;
2. inductive and capacitive crosstalk between signal pairs;
3. time- and frequency-domain measurements;
4. high-frequency component modeling and high-frequency filter design;
5. common-mode radiation studies (under development); and,
6. electrostatic discharge, radiation prevention, transient suppression (to be developed).

Students learn in the first laboratory exercise that the impedance in a circuit at frequencies greater than a few

kilohertz is typically dominated by the inductance of the current loop. A coiled RG-58 cable and a ground strap is employed to provide two current paths, one with an appreciable loop area but low series resistance, and one with small loop area, but larger series resistance. The relative current levels for each path are measured as a function of frequency, and students learn that inductance associated with appreciable loop areas can dominate the impedance of a circuit at relatively low frequencies.

Students review the crosstalk experiment conducted in the second semester introductory course, and then go on to look at practical crosstalk measurements in intersystem cabling. Side-by-side, separated, coaxial cable, and twisted shielded pair conductors are investigated. Students obtain estimates of the mutual inductance from measurements for each signal conductor configuration.

Students investigate the frequency content of high-speed digital pulses in the third laboratory. The rise-time of a trapezoidal pulse is measured with a high-speed oscilloscope, as well as the pulse spectrum with a spectrum analyzer. Students compare the measured spectrum with theoretical calculations. Inductive and capacitive filtering strategies are investigated, and the effect of the rise-time and resulting pulse spectrum is measured.

In the fourth experiment students study the non-ideal behavior of lumped elements at high frequencies as a result of parasitic inductance, capacitance, and resistance. A network analyzer is employed to measure the insertion loss of individual inductors and capacitors comprising a T-filter. They then construct equivalent circuit models of individual elements, and these models are employed to construct an equivalent model for the T-filter. The insertion loss of the T-filter is measured, and the measurements compared with the developed equivalent circuit model.

Two of the above experiments are yet to be developed, common-mode radiation studies, and ESD investigations. Both will build on experiments in the two earlier courses.

In the laboratory component of all three courses, learning to organize and present technical material is an important aspect. In each course, one publication quality technical report on a specified experiment is required. Students must discern the important information to include in the report, and present it in a clear and concise manner that demonstrates good technical writing development and technical competence.

4 Acknowledgements

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5 Appendix: A Fields and Waves II Experiment

Magnetic-Field Coupling (Faraday's Law) and Inductance

Objectives:

1. To understand mutual coupling through the magnetic field and practical implications of Faraday's law in hardware;
2. to investigate and measure the inductance associated with signal wires; and,
3. to develop equivalent circuit models for the test configurations.

Equipment:

- 1 Function Generator
- 2 Tektronix 2230 Oscilloscope
- 3 HP4815A Vector Impedance Meter
- 4 HP4262A LCR Meter
- 5 Multi-turn wire loops: 11 cm (2), 7 cm, 5.5 cm, and 4 cm diameters.

Coupling Through the Magnetic Field – Faraday's Law

According to Faraday's law, a time-varying magnetic field through a surface bounded by a closed path induces a voltage around the loop. This fundamental principal has important consequences for parasitic coupling in electronic hardware. For example a "noisy" circuit on a printed circuit board may produce a significant time-varying magnetic field as a result of current levels and current loop area. This magnetic field through the loop area (determined by the signal current) of a susceptible or "victim" circuit induces a voltage in the victim circuit. Depending upon the source and load impedances in the victim circuit, loop area, distance between the victim and noise emitter circuits, and orientation of the circuits, this coupling can cause faulty operation of the victim circuit. Coupling between circuit loops through the time-varying magnetic field is studied this section.

Experiments:

The test configuration for the following experiments is shown in Figure 1.

1. For the four diameters of receiver loops, 11, 7, 5.5, and 4 cm, and a separation between the loops of $d = 0$, measure the voltage developed across the terminal of the receiver loop (secondary). Adjust the amplitude of the source to obtain approximately $3 V_{p-p}$ measured across the 10Ω resistor in the source loop using an 11 cm diameter loop. Use a sinusoidal source with frequency of 1 MHz. Plot the peak-to-peak voltage V_{p-p} (ordinate) at the terminals of the receiver loop versus area (abscissa). Is this function linear? Is it expected to be?

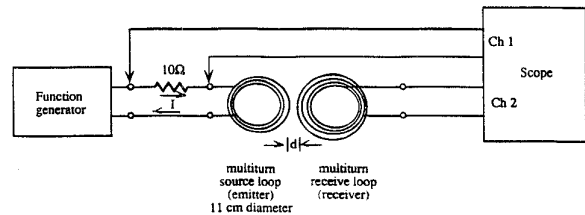


Figure 1: Experimental configuration for studying coupling between circuit loops through a time-varying magnetic field.

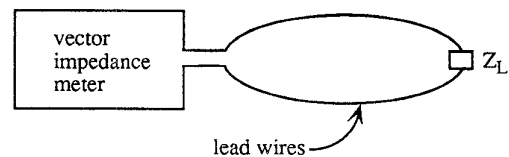


Figure 2: Orientation of emitter and receiver loops.

2. For the 11 cm diameter receiver loop, plot V_{p-p} at the terminals of the receiver loop (ordinate) versus distance d (abscissa). Use an 11 cm diameter source loop. Acquire no more than six data points. What is the functional variation of this curve? Is it $\frac{1}{r}$? Why or why not?
3. Investigate the coupling for the orientations of emitter and receiver loops shown in Figure 2 for two 11 cm diameter loops.
4. Using the 11 cm receiver loop, place this on top of the 11 cm emitter loop (axes coincident), and plot the measured voltage V_{p-p} in the receiver loop as a function of the distance R between the two loop centers as the receiver loop is moved off the emitter loop.
5. For $R = 0$, as in Part 4 above, apply a square wave from the source, and investigate the relationship between the source signal (Channel 1 of the scope) and the receiver loop signal (Channel 2). Use the 11 cm loops for both the emitter and receiver. How are these two signals related? Is this expected? Note the non-ideal behavior (rounded) of the "square"-wave. Suggest causes for this.

Inductance in Wires, Traces, and Cabling

The wires, traces, and cabling interconnecting circuits and systems has an inherent inductance associated with the loop area of the current path. At megahertz and hundreds of megahertz frequencies, the resulting impedance

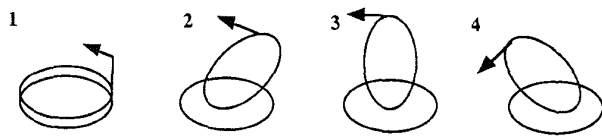


Figure 3: Experimental configuration for investigating the inductance associated with wires.

$Z_L = j\omega L$ for this inductance is significant, and can dominate the frequency response of the circuit.

Experiment:

The experimental configuration is shown in Figure 3.

1. Measure the impedance of a $50\ \Omega$ resistor with the vector impedance meter (resistor at the meter probe). Measure the $50\ \Omega$ resistor attached to $40\ \text{cm}$ untwisted wires (spread to minimize the mutual capacitance). Measure the impedance of the $40\ \text{cm}$ untwisted wires shorted at the end. Measure the impedance for each configuration at 0.5 , 2 , 10 , 20 , and $40\ \text{MHz}$. Develop an equivalent RL circuit model, where L is the inductance in the "cabling". Approximate the inductance in the cabling from the above measurements. At what frequency does the inductance begin to dominate the circuit, i.e., at what frequency does the impedance of the equivalent inductance for the cabling become larger than the resistor?
2. An alternative approach to approximating the inductance in the cabling is to resonate this inductance with a capacitance. Attach a $100\ \text{pF}$ capacitor to the $40\ \text{cm}$ untwisted wires (spread). Model this configuration with an equivalent series RLC circuit. (The R comes from small losses in the wire and capacitor.) Measure C with the LCR meter. Determine the series resonance frequency for the circuit by measuring Z_{in} as a function of frequency. Series resonance is when $\Im\{Z_{in}\} = 0$, or equivalently when $\angle Z_{in} = 0$. Determine L from the resonance frequency and the measured value of C . Does it compare well with the previously measured value?

Lab Report

Your design group is measuring some rather severe noise coupling problems in a prototype circuit. Because of inattention to large circuit loops and segmented ground planes, you suggest that the noise problems could stem from coupling through the magnetic field. However, your engineering manager does not fully see the implications that Faraday's law can have in practical design. You have constructed this demonstration to convince him or her that this could very likely be the problem. After giving your boss a short demonstration (the lab), you must prepare a five page summary to convince him or her that more attention should be given to minimizing loop areas in circuit layouts because of the large self inductance, and

the potential for noise coupling through the magnetic field.

Grading:

- 1 Appearance (20%)
- 2 English Grammar (20%)
- 3 Organization and Content (20%)
- 4 Technical Merit (40%)

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