The Use of Numerical Modeling Tools to Foster Practical Insight into the Mechanisms of Electromagnetic Interference and Its Control

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Abstract

The control of electromagnetic interference (EMI) is becoming increasingly vital as electronic equipment operates at higher speeds and wireless communication services command larger portions of the spectrum. Although EMI has not been traditionally included in the engineering curriculum, many institutions have established such courses in the past decade to help meet the demands of industry. The concepts encompassed by EMI span both circuit and electromagnetic theory and require a good deal of visualization. Several numerical modeling tools developed for use in EMI research have been adapted to EMI education in order to give the students experience in picturing the mechanisms of EMI generation. Once the mechanisms are understood, the remedies and their principles of operation can be recognized and tested. This paper describes some of the materials and exercises created for courses in EMI control using numerical electromagnetic modeling tools to create a visual presentation of the process of EMI generation.

Introduction

The demands on the electromagnetic spectrum placed by the ever increasing needs for telecommunications coupled with the dramatic rise in computer clock speeds have made the control and mitigation of electromagnetic interference more imperative than ever. Governmental agencies around the world place strict limits on the level of emissions from electronic products. Products that do not comply with these regulations cannot by legally sold; hence, manufacturers have been making considerable investments in EMI control. Products that meet all applicable requirements are said to have achieved electromagnetic compatibility (EMC). Although not part of the traditional electrical engineering curriculum, many schools have instituted courses [1] to help meet the demand for EMC engineers.

The field of EMC bridges electromagnetic and circuit theory. Much can be learned by examining the solutions to the handful of canonic problems with idealized geometries, but closed form solutions generally do not exist in practical situations. Laboratory exercises can help teach practical principles and many useful experiments and demonstrations have been developed [2]. The experiments must be carefully constructed because EMI measurements are often difficult to make and are subject to a host of errors that can confuse the students. Under the right conditions, students can gain valuable experience by making hands-on measurements, but the relatively expensive facilities needed for quality measurements can be used by only small groups of students at any one time. Numerical electromagnetic modeling programs with the right interfaces and set of instructive applications can provide the students with visual examples and another means of experimentation among various design alternatives. These pedagogical tools help the students to

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begin to develop a more intuitive understanding of the various mechanisms and mitigation techniques for the control of EMI.

Computer Tools

The widespread availability of high-speed computers has made the realistic simulation of electromagnetic field generation and propagation a practical possibility. Many programs based on well-developed full-wave analysis techniques such as the method of moments, the partial-element equivalent circuits (PEEC), finite elements, and finite difference time domain (FDTD) are available. The task of the instructor is to adapt these tools for use by students who have only a limited background in the concepts of electromagnetics. The students have considerably more experience with traditional circuit analysis; wherever possible the electric and magnetic field coupling mechanisms are explained using the lumped elements of mutual capacitance and mutual inductance. Because it explicitly models the electric and magnetic field coupling with these elements, the PEEC method [3] is particularly helpful in this regard and simplifies the integration of an electronic circuit into the electromagnetic analysis.

Two programs, written by the author for research in electromagnetics, were adapted for use in the teaching of EMC. The first of these is a PEEC program that allows the specification of the physical geometry of a circuit layout or structure and the insertion of lumped elements [4]. The students need not be concerned with the inner workings of the program. It is used to teach the relationships between the physical structure of a circuit and a) its pattern of current distribution and b) its radiated emissions. Figure 1 displays a schematic of the PEEC program. The user enters a description of the circuit geometry as a series of rectangular plates, the circuit elements by value, and the location of each element connection. The two principal outputs of the program are a current map across the layout of the circuit and the radiated electric-field pattern in planar cuts computed at a far-field distance. The program supports multi-layer circuits, and its current maps are color-coded by current density. Each layer of the circuit is selected for individual display. In this way, the distribution of the current flowing in a ground layer may be readily seen. Students can use the PEEC program to run a series of experiments to examine the effect of various layout strategies or parameters such as termination impedances or frequency. The students can gain a sense of the relationship between different current distributions and their corresponding radiated emissions by examining far-field patterns computed from the currents flowing in the PEEC elements.

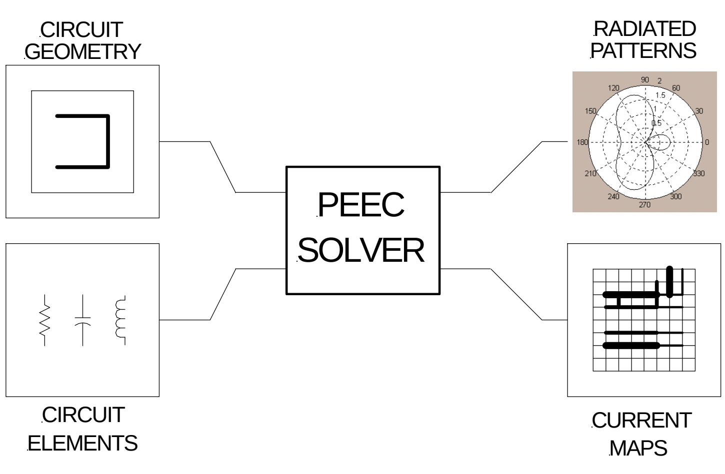

Figure 1 Schematic of the PEEC analysis program.

The second program is based on the method of moments and has been used to compute the current distributions and maps of both field intensities and the shielding effectiveness of various structures. The input geometry is described as a coordinate list specifying the locations of the vertices and the sources in the structure. From this description, the program computes the current flow on every conductive surface. This array of currents allows the electric field at any point in space to be calculated and is used to make color coded field maps over a specified area. The maps display either the total field in dBV/m or the shielding effectiveness in dB, which is computed by comparing the fields calculated with and without the metallic surfaces of the structure present. The color-coding makes the areas of relatively high and low intensity readily apparent. At this time, the mapping program is only used to produce instructive figures for class presentations, because the input method is not yet developed enough for general use by the students.

Pedagogical Applications

The principal job of an engineer designing products for EMC is the orchestration of current flow to produce a minimum of emissions. Hence, a key to EMC education is the development of the ability to visualize the paths taken by the current from a load back to its source. A design that is unconcerned with EMI pushes the return current into the "ground" system (as shown on a circuit schematic) and assumes that it automatically makes it back to the source in some fashion. In practice, the actual path(s) followed by the return current can have a major effect on the emissions radiated by the circuit. The PEEC computer program was used to create example exercises and presentations to illustrate the principles of return-current flow.

Return Current in a Circuit Layout

A ground plane on a printed-circuit card provides a myriad of paths for return current flow, and it is useful for the designer to understand the apportionment of the current among the paths. At low frequencies, the return current distributes itself in accordance with the relative resistances of the paths. At high frequencies, the division occurs according to the relative inductance of each path. As an instructive example, the students can analyze the two-layer configuration shown in figure 2 where a source drives a load through a trace on the top layer and the current is expected to return in the ground plane on the backside layer. At the low frequency of 60 Hz, the return current will tend to follow a straight-line path from the source to a load. At a much higher frequency, the current in the ground plane will tend to stay directly below the top-layer trace because that is the path of least inductance. Figure 3 displays this behavior at an excitation frequency

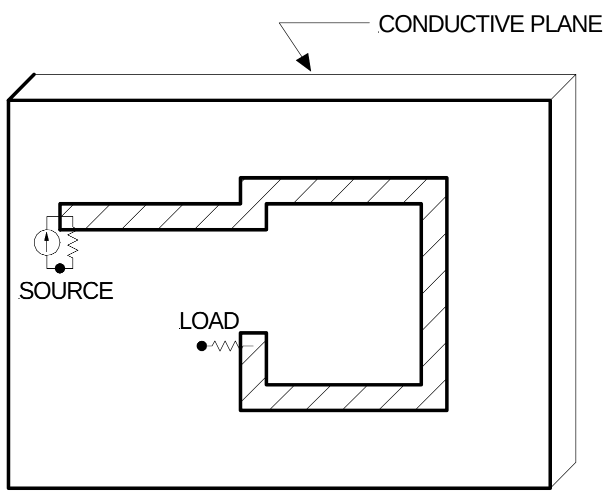

Figure 2 Printed-circuit card configuration used for return current example.

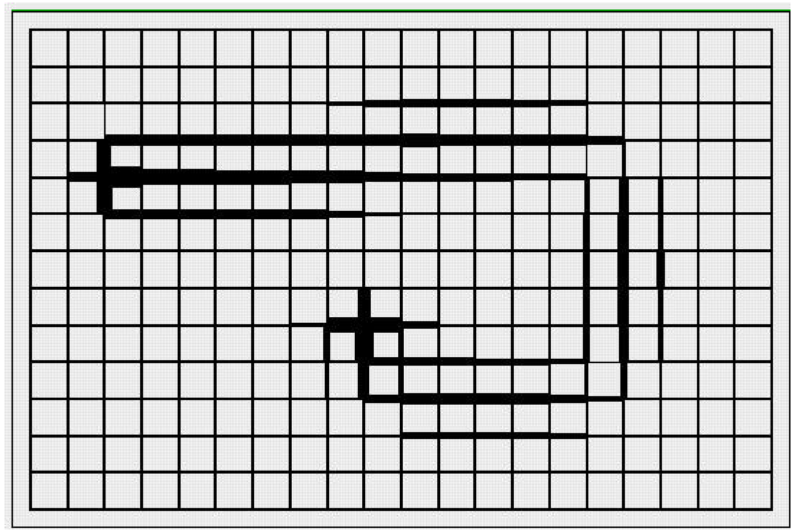

Figure 3 Current map for return flow in the layout of figure 2.

of 50 MHz. Due to the monochronicity requirements of this publication, the width of the trace in the figure is proportional to the current density. The actual computer display seen by the students also uses a color map to represent more dramatically the current density with brighter colors identifying the regions of greatest current. One of the first exercises is to determine the boundary between “low” and “high” frequency by experimentation. The boundary is, for typical geometries and copper conductors, in the frequency region of 10 kHz.

The natural tendency for current to follow the path of least inductance is beneficial for EMI control because the amount of magnetic flux produced by a given current is proportional to inductance. Hence, producing

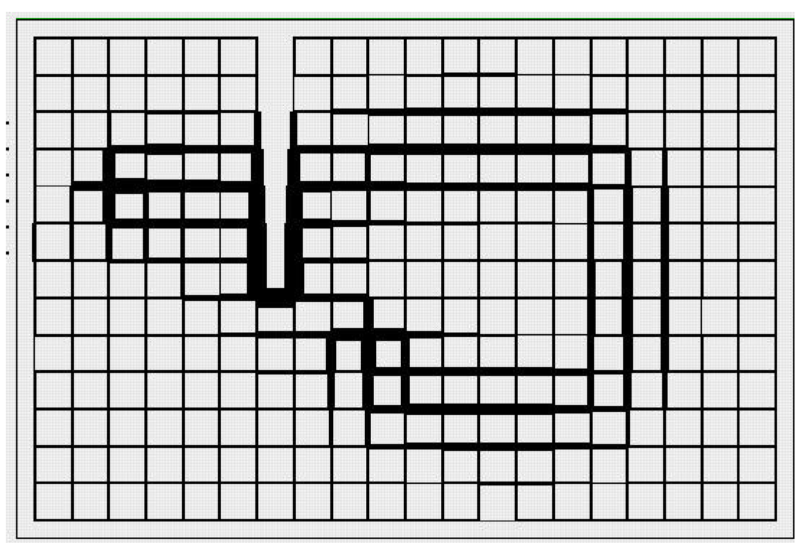

Figure 4 Disruption of return current flow by a slot cut into the conductive plane.

less flux connotes lower radiated emissions. The students can verify this hypothesis by placing a slot in the ground plane so that the current must bend around it, thereby increasing the inductance of the return path. Figure 4 depicts the ground-plane current distribution in the presence of such a discontinuity. The radiated emissions are computed with and without the slot to show that the more inductive path produces a higher level of emissions. In this example, the arrangement of figure 4 produces an additional 6 dB in the far field at 50 MHz over the layout of figure 3.

Return Paths in a Ribbon Cable

The application of interconnect cables is another area where the control of return current is vital to achieve low emissions. The PEEC program can be used to experiment with various configurations for bringing the return current back to the source. A good and practical example is an exercise that involves the assignment of “ground” conductors in a ribbon cable that is carrying signals between two assemblies. Figures 5a and 5b illustrate two different arrangements in an eight-conductor cable where S and G denote signal and ground leads, respectively. In configuration a) only a single ground wire is used and in part b) a ground wire is placed between every two signal conductors. The current flows were computed by exciting the signal conductor on the left in each case and are displayed in figure 6. In configuration a), the return current must flow in the single ground conductor located on the right. When more ground leads are provided as in configuration b), most of the current flows in the ground conductor that is adjacent of the signal lead because that is the path of least inductance, and the overall inductance is less than configuration a). The distribution of the ground leads also has a noticeable effect on the crosstalk between signal leads. For example, observe in each case the current in the signal that is carried by the third conductor from the left that is induced by the excitation current flowing in the left signal lead. In configuration a) the overall inductance driven by the current is less than that of configuration b). The corresponding result in this example is a reduction of 11 dB in the radiated emissions by distributing the ground leads.

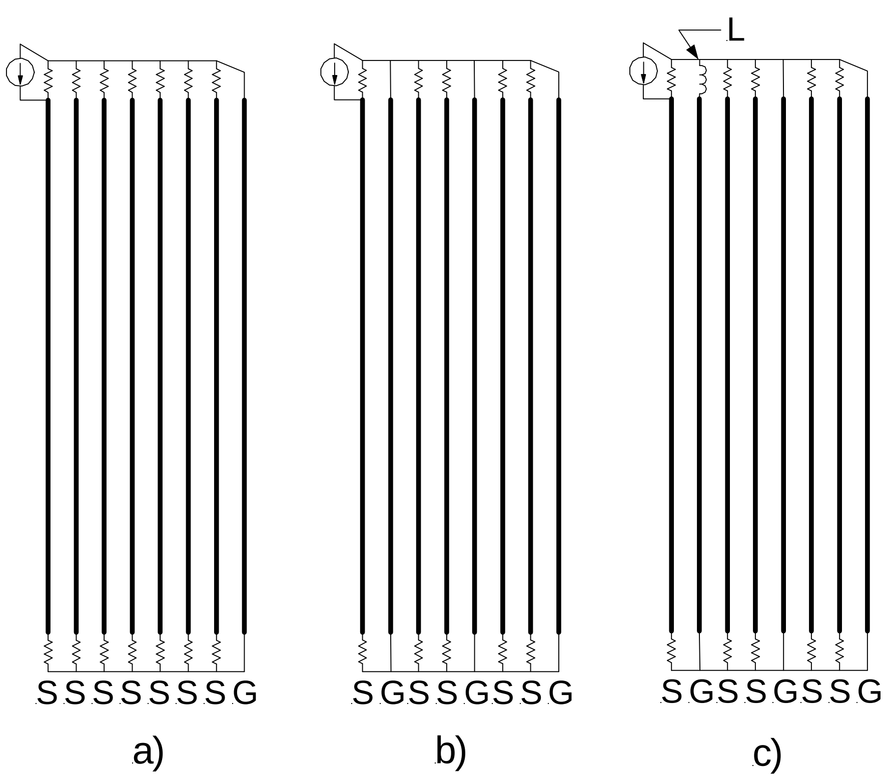

Figure 5 Configurations for three ribbon cable examples.

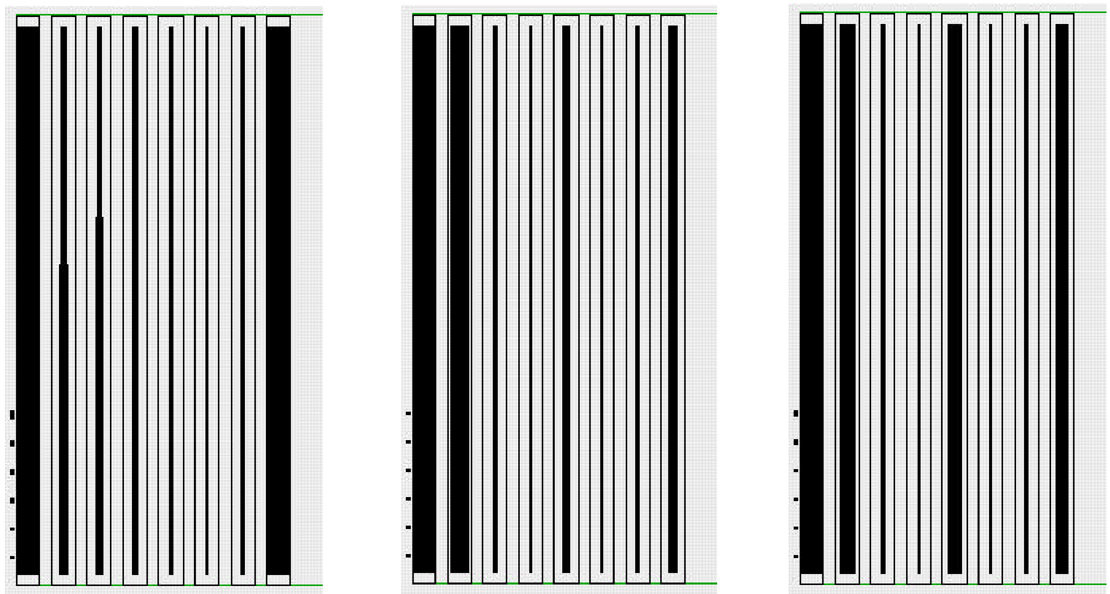

Figure 6 Computed current maps for the ribbon cable examples a), b), and c) in figure 5.

The physical connection of the ground lead of the cable to the actual source of current is also crucial. To illustrate, figure 5c shows an inductance (L) between the ground return of lead 2 and the current source driving the first signal lead. Physically this inductance represents excessive length or a meandering connection line between the cable connection header and the circuit driving the signal. In this example, a value of 100 nH of excess inductance was used and made it less attractive for the return current to flow in the second conductor. The resulting current distribution (example C in figure 6) shows that much of the return current has been diverted to the other two ground leads. The corresponding increase in radiated emissions computed in this example is 4 dB over configuration b).

Shielded Enclosures with Apertures

Another major area of EMC is the design of shielded metallic enclosures that are used to attenuate emissions from the circuitry mounted inside of them and to protect that circuitry from strong external emissions. A first guess at predicting the behavior of waves in the presence of a shield is to use ray tracing, but this method is not successful because it does not account for diffraction. Thus, the students need to be shown how waves bend around the edges and through the apertures of the shield. Further, they need to understand how reflections create resonances inside the enclosure and other standing waves in order to design cost-effective shields [5].

Shielding effectiveness (S) is defined as the ratio of the field measured without the shield to the field measured with the shield installed and is ordinarily expressed in dB. In addition to the design of the shield, S depends on frequency and the observation point. Except in the cases of very low frequency magnetic fields, or very thin metal such as conductive paint applied to plastic, the electromagnetic energy does not penetrate directly through the shield wall. Instead the effectiveness of most enclosures is set by discontinuities in the shield—the apertures and seams. To demonstrate these concepts and to enable the students to visualize the operation of a shield, the method-of-moments program described above was used to produce maps of

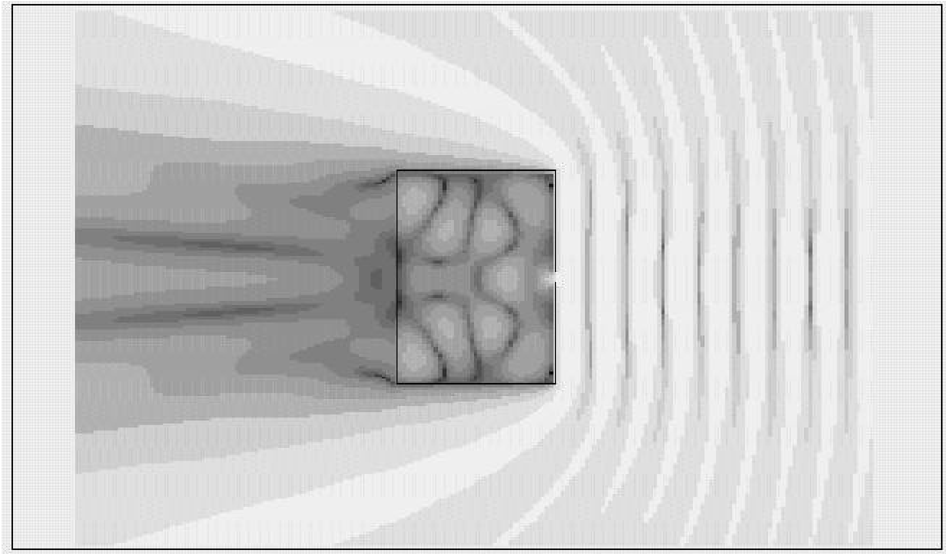

Figure 7 Map of the shielding effectiveness in a rectangular shield with illuminated aperture. The scale on the left is *S* in dB.

shielding effectiveness across an observation space. These maps are presented during the lectures and color keyed with darker colors representing regions of greater shielding effectiveness (and hence, less field intensity). Although not shown here, a calibration table by color for the shielding effectiveness in dB is given. As an example, figure 7 displays *S* in a cross-sectional view for a (50×75×50 cm) rectangular shield with a single (6.3×6.3 cm) square aperture that is illuminated by an 850 MHz source located 10 m to the right of the shield (outside the region of the map). The pattern of *S* shows the diffraction of the wave around the edges of the shield and the shadow cast behind it. It also reveals that in the shadow the waves are not completely attenuated, owing to the diffraction, and that the shadow is darkest in the area directly behind the shield. The spatial pattern inside the shield is indicative of the resonance of the chamber. This display demonstrates to the students that once electromagnetic energy has entered a shielded enclosure, it may intensify at many points due to constructive interference caused by multiple reflections of the wave. In other words, the region of poorest shielding effectiveness is not just in the area right behind the aperture; the resonant behavior degrades *S* over much of the enclosure.

Another notable phenomenon appears in the region in front of the shield—a standing wave. The peaks of the standing wave exhibit a negative shielding effectiveness of up to –6 dB. In other words, the field intensity in these bands is actually as much as twice as strong in this region with the shield present than without, owing to constructive interference at these points between the incident and reflected waves. Hence, the students learn that using a shield to protect a particular volume in a product can intensify the fields in other regions. This behavior is not a fatal flaw in the application of a shield, but its points up potential problems that might be created when sensitive circuitry is placed in the standing wave area.

Various parametric changes are demonstrated to the students using the shielding effectiveness maps. For instance, as long as the maximum linear dimension of the aperture is less than one half of a wavelength as it is in this example, it behaves like a waveguide below its cutoff frequency. Increasing the depth of the aperture using the boss detail shown in figure 8 results in some additional attenuation. The minimum shielding effectiveness inside the enclosure without the boss (figure 7) is 11 dB and with a 1 cm boss in figure 8 it is 15 dB.

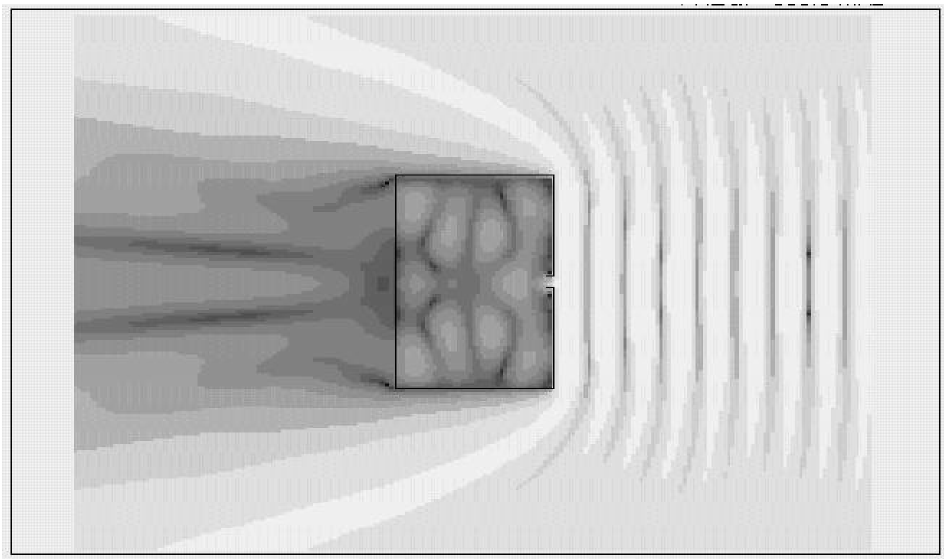

Figure 8 Map of *S* with a 1-cm aperture boss.

Summary

Learning to control electromagnetic interference can be difficult because the behavior of electromagnetic waves is an abstract concept for most students. To place the theory in a more practical framework, two electromagnetic analysis programs were modified and used to create instructive presentations and exercises. These materials enable students to visualize the behavior and mechanisms of EMI in terms of current flow and wave behavior. Future work will include updating and improving the user interfaces of both programs in order to increase the number and types of experimental exercises that can be performed by students working on their own.

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