Engaging Students in Electromagnetics through Hands-On Skills and Computer Simulation

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Abstract - Electromagnetics has always been among the most difficult courses in electrical engineering and physics, and consequently, innovative teaching techniques are necessary to change the way teachers teach and students learn. The electronics engineering technology program in the University of Southern Mississippi has been offering an optional applied electromagnetics course as well as imbedding electromagnetics concepts into lower level electronics courses for several years. The students' interest in electromagnetics has increased through new teaching and learning styles. This paper introduces in detail a new practice where students learned electromagnetics through projects. Particularly, in one of the projects, students designed and implemented an electromagnetic can crusher. In addition to hands-on skills, theory and computer simulations were also involved. Students worked in a group to construct an electromagnetic can crusher, while the instructor introduced the theory and computer simulation process.

This paper gives details about the theoretical aspect of the lecture, including derivation of necessary formulas used for computer simulation. A survey was conducted to ascertain the reactions of the students towards this mode of teaching and learning. Results showed that students learned by cooperating and interacting with each other and participated actively in their own learning process. Students also learned to cultivate teamwork, communication, management and interpersonal skills.

Keywords: Electronic Engineering Technology (EET), electromagnetics education, student-oriented, project-based, electromagnetic can crusher

1 Introduction

Problems in electromagnetic (EM) fields and waves are getting more and more important as they arise in diverse areas such as radar systems, antennas, communication systems, electrical machines and apparatus, PCB, RFIC, RFID, Bluetooth, and other mobile techniques. However, because of its nature of abstract math and physics, electromagnetics is generally very challenging and demanding, even for well-motivated students majoring in electrical engineering that have a fair amount of preparation in the required math and physics courses. There are a great many of pedagogic practices in EM education, most of which can be classified into one of the three: traditional classroom lectures, hands-on experiments and projects, and simulation and multimedia tutorial software packages. While classroom lecturing is still the main stream practice, simulation and visualization tools, including some popular commercial computer aided EM software and those produced in house by various university faculty have been employed for efficient electromagnetics education [1,2]. Among the great many of reports in literature on electromagnetics education, most of them are for undergraduate and graduate level students in EE program, [3]. Few have focused on electromagnetics education of electronic engineering technology (EET) students. Electromagnetics is not traditionally considered a typical EET course, due to the obvious distinction between EE and EET programs. Generally speaking an EE curriculum is more theoretical; EET curriculum is more focused on an experience-building learning style and appeals to students who learn best by their hands-on experience. Electronic engineering technology programs prepare students for practical design and production work, therefore, EET curricula focus on more practical applications and technical information instead of theoretical views.

The electromagnetics education in undergraduate electronics engineering technology curriculum at the University of Southern Mississippi can be traced back to about ten years ago. First, EM concepts have been introduced into non-EM courses [4–6], and then an innovative student-oriented, seminar-based classroom practice [7] has been adopted in the following EM courses, which was illustrated by student-oriented theoretical inquiry of interested topics combined with traditional and emerging applications.

In this paper, a project based delivery is introduced. Under the careful guidance of the instructor, every student or student group chose to implement an EM project of their interest. One good example is the electromagnetic can crusher. It is a popular device for demonstration of electromagnetic forces to students interested in electromagnetics [8], though detailed calculation and computer simulation is, to the knowledge of the author, not available in literature. The formulation and computer simulation was provided by the instructor and the project was implemented by the students.

The paper is organized as follows: after the introduction the formulation is derived in section II, and the simulation results are presented in section III. Section IV provided student survey results about the learning outcomes, followed by conclusion in the last section.

2 Problem Statement and Formulation

The electromagnetic can crusher uses very basic principles of electricity and magnetism. First, a capacitor is charged to a high voltage, and then is discharged through a coil of several turns of wire tightly wound around the center of the soda can. This discharge creates a magnetic field around the coil. As the flux lines pass through the cross section of the can, current is induced and flows around the can. The induced current generates Lorentz force that pushes inward on the can and outward on the coil. Once the force is strong enough the can is crushed.

From Maxwell equations

$$\begin{cases} \nabla \times \mathbf{E}(\mathbf{r},t) = -\mu \frac{\partial \mathbf{H}(\mathbf{r},t)}{\partial t} \\ \nabla \cdot \mathbf{E}(\mathbf{r},t) = \frac{q_v^i(\mathbf{r},t)}{\varepsilon}; \\ \nabla \times \mathbf{H}(\mathbf{r},t) = \varepsilon \frac{\partial \mathbf{E}(\mathbf{r},t)}{\partial t} + \mathbf{J}^i(\mathbf{r},t); \\ \nabla \cdot \mathbf{H}(\mathbf{r},t) = 0, \end{cases} \tag{1}$$

The magnetic flux density $\mathbf{B}$ can be obtained from

$$\mathbf{B} = \nabla \times \mathbf{A}, \tag{2}$$

where vector potential $\mathbf{A}$ can be calculated by

$$\mathbf{A}(\mathbf{r}) = \frac{\mu}{4\pi} \int_C \frac{\mathbf{I}(\mathbf{r}')}{R} dl'. \tag{3}$$

In the equation, quantities with and without prime signs represent quantities for source and field points. R is the distance between a source point and a field point.

In this problem, cylindrical coordinate system (ρ, ϕ, z) is preferred to any others because of the shape of the structure.

2.1 Vector Potential

Assuming the coil has a radius a and pitch p, then

$$R = \sqrt{a^2 + \rho^2 - 2a\rho\cos(\theta - \theta') + \left(z - \frac{p}{2\pi}\phi'\right)^2}. \tag{4}$$

The current I flowing through the coil of k turns has only two components in the ϕ and z direction, i.e.

$$\mathbf{I} = \hat{\mathbf{a}}_\phi I_\phi + \hat{\mathbf{a}}_\mathbf{z} I_z, \tag{5}$$

where

$$I_\phi = \frac{2\pi a}{\sqrt{(2\pi a)^2 + p^2}} I; I_z = \frac{p}{\sqrt{(2\pi a)^2 + p^2}} I. \tag{6}$$

Therefore, $\mathbf{A}(\rho, \phi, z)$ has two components in the ϕ and z direction, i.e.

$$\mathbf{A}(\rho, \phi, z) = \hat{\mathbf{a}}_\phi A_\phi + \hat{\mathbf{A}}_\mathbf{z} I_z, \tag{7}$$

where

$$A_\phi = \frac{\mu}{4\pi} \frac{2\pi a I}{\sqrt{(2\pi a)^2 + p^2}} \int_0^{2\pi k} \frac{1}{\sqrt{a^2 + \rho^2 - 2a\rho\cos(\theta - \theta') + \left(z - \frac{p}{2\pi}\phi'\right)^2}} d\phi', \tag{8}$$

and

$$A_z = \frac{\mu}{4\pi} \frac{pI}{\sqrt{(2\pi a)^2 + p^2}} \int_0^{2\pi k} \frac{1}{\sqrt{a^2 + \rho^2 - 2a\rho\cos(\theta - \theta') + \left(z - \frac{p}{2\pi}\phi'\right)^2}} d\phi'. \tag{9}$$

2.2 Magnetic Flux Density

The magnetic flux density can be calculated by

$$\mathbf{B}(\rho, \phi, z) = \frac{1}{\rho} \begin{vmatrix} \hat{\mathbf{a}}_\rho & \rho\hat{\mathbf{a}}_\phi & \hat{\mathbf{a}}_\mathbf{z} \\ \frac{\partial}{\partial \rho} & \frac{\partial}{\partial \phi} & \frac{\partial}{\partial z} \\ A_\rho & A_\phi & A_z \end{vmatrix} \tag{10}$$

or

$$\mathbf{B}(\rho, \phi, z) = \hat{\mathbf{a}}_\rho \left[\frac{1}{\rho}\frac{\partial A_z}{\partial \phi} - \frac{\partial A_\phi}{\partial z}\right] - \hat{\mathbf{a}}_\phi \frac{\partial A_\phi}{\partial \rho} + \hat{\mathbf{a}}_\mathbf{z} \left[\frac{\partial A_\phi}{\partial \rho} + \frac{1}{\rho} A_\phi\right]. \tag{11}$$

2.3 Magnetic Flux

The magnetic flux passing through a horizontal plan is given by

$$\Phi = \iint_S \mathbf{B} \cdot d\mathbf{s} = \oint_{\partial s} \mathbf{A} \cdot d\mathbf{l}. \tag{12}$$

The magnetic flux passing through the can cross section is

$$\Phi_{in} = \oint_{\partial s} \mathbf{A} \cdot d\mathbf{l} = \frac{\mu}{4\pi} \frac{2\pi a I}{\sqrt{(2\pi a)^2 + p^2}} \int_0^{2\pi} \int_0^{2\pi k} \frac{d\phi' c d\phi}{\sqrt{a^2 + \rho^2 - 2a\rho\cos(\theta - \theta') + \left(z - \frac{p}{2\pi}\phi'\right)^2}}; \tag{13}$$

The magnetic flux through the coil cross section is

$$\Phi_{out} = \oint_{\partial s} \mathbf{A} \cdot d\mathbf{l} = \frac{\mu}{4\pi} \frac{2\pi a I}{\sqrt{(2\pi a)^2 + p^2}} \int_0^{2\pi} \int_0^{2\pi k} \frac{d\phi' a d\phi}{\sqrt{a^2 + \rho^2 - 2a\rho\cos(\theta - \theta') + \left(z - \frac{p}{2\pi}\phi'\right)^2}}. \tag{14}$$

2.4 Induced Current and Lorentz Force

The induced current flowing on the surface of the can is

$$\mathbf{I_{can}} = -kI\frac{\Phi_{in}}{\Phi_{out}}. \tag{15}$$

The Lorentz force is

$$\mathbf{F} = \int \mathbf{I_{can}} d\mathbf{l} \times \mathbf{B} \tag{16}$$

The force has three components:

$$F_\rho = -kI\frac{\Phi_{in}}{\Phi_{out}} c \int_0^{2\pi} \left[B_z - \frac{p}{2\pi a} B_\phi\right] d\phi, \tag{17}$$

$$F_\phi = -kI\frac{\Phi_{in}}{\Phi_{out}} c \int_0^{2\pi} \frac{p}{2\pi a} B_\rho d\phi \tag{18}$$

$$F_z = kI\frac{\Phi_{in}}{\Phi_{out}} c \int_0^{2\pi} B_\rho d\phi \tag{19}$$

3 Computer Simulation and Numerical Results

The formulas derived in the last section are coded in Matlab platform and the electromagnetic process is simulated on a desktop computer. The simulation takes the following configurations: radius of coil is 0.0381 meters; number of turns is 5; pitch is 0.01 meters; the radius of the can is 0.03175 meters; the height of the can is 0.1222 meters.

The current flowing through the coil needs to be computed or measured in the future. Here it is assumed to be 1000 amperes in this simulation.

The algorithm is discretized in 100 segments along axial direction, 100 segments along azimuthal direction, and 100 segments in vertical direction. When integrating the source contributions numerically, 100 segments are used. Exact integration over the singularity will be considered in the future.

All the results discussed in the last section were simulated on computer, while examples of the results are showed below.

3.1 Magnetic Flux Density

Magnetic flux density is the amount of magnetic flux through a unit area taken perpendicular to the direction of the magnetic flux. The three components of the magnetic flux density along the $x-$axis or the radial direction of the soda can are plotted in Figure 1.

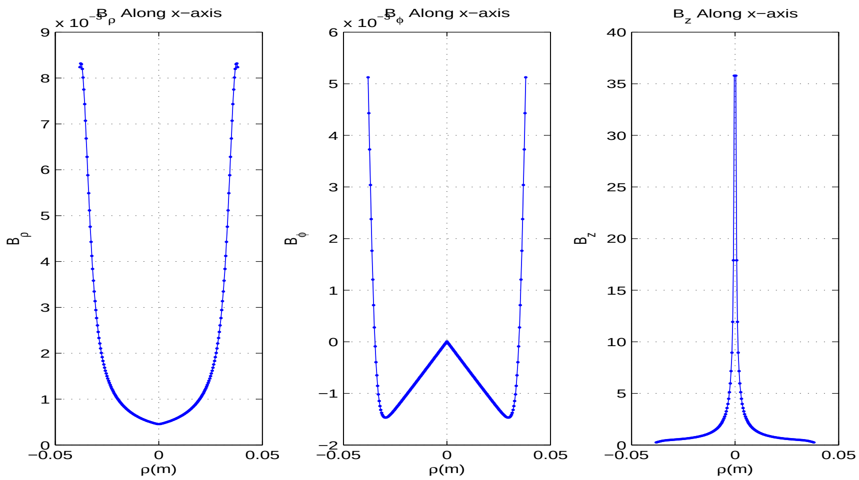

Figure 1: Magnetic flux density

3.2 Magnetic Flux

The magnetic flux through a surface is the component of the **B** field passing through that surface. The total magnetic flux through the whole cross section along the $z-$axial or the axial direction of both the coil and the soda can are plotted in Figure 2.

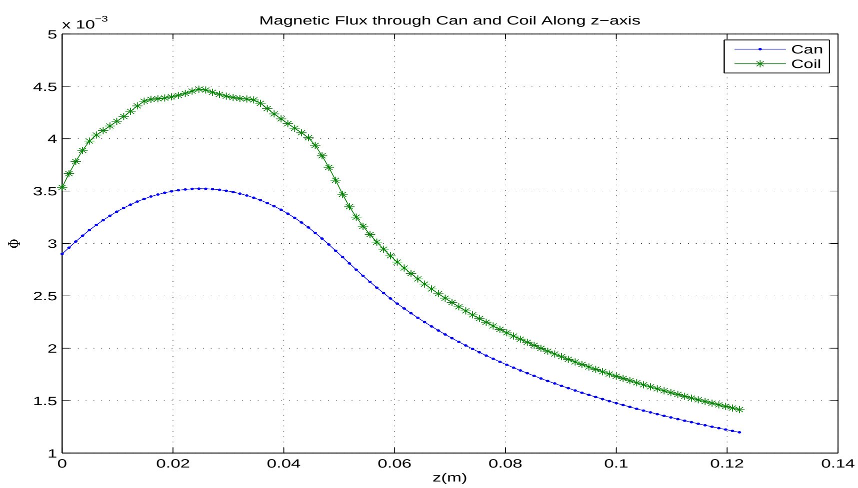

Figure 2: Magnetic flux

3.3 Lorentz Force

Because the induced surface current on the soda can are immersed in the magnetic fields generated by the coil, Lorentz force is generated. The Lorentz force to the whole perimeter of the soda can along the $z-$axis or the axial direction is calculated and plotted in Figure 3. As the positive direction is set along the radical direction, a negative force means the direction of the force is inward, thus the can will be crushed.

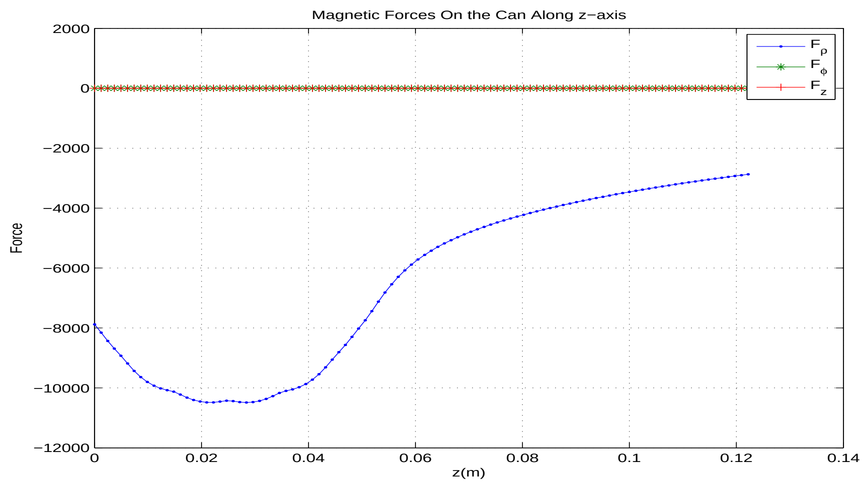

Figure 3: Lorentz force

4 Hardware Implementation

The energy is stored in a capacitor bank, which uses Aerovox M 4200μF 450VDC capacitors and RIFA 3300μF 420VDC capacitors connected in series in order to get 800VDC of voltage. The power plug is connected to an AC relay with a switch to turn it on and off, which keeps the charging and discharging circuits separated from each other. The discharge circuit consists of two metal plates brought together by a solenoid. The round red button on the top of the table twists to enact the discharge and pushes back down to release it. A digital volt meter is used to show the voltage on the capacitors. A prototype is showed in Figure 4.

5 Student Survey on the Learning Outcomes

A set of questionnaire was distributed to the class to obtain student's opinion of the class. Example questions includes

- How do you think the project-based teaching method in the class?
- Do you prefer the traditional or project-based delivery methods?
- As an engineering technology student, which way gives you a better learning outcome?
- How does the course affect the students' performance on future, life-long development, such as study new techniques and pursue graduate studies?

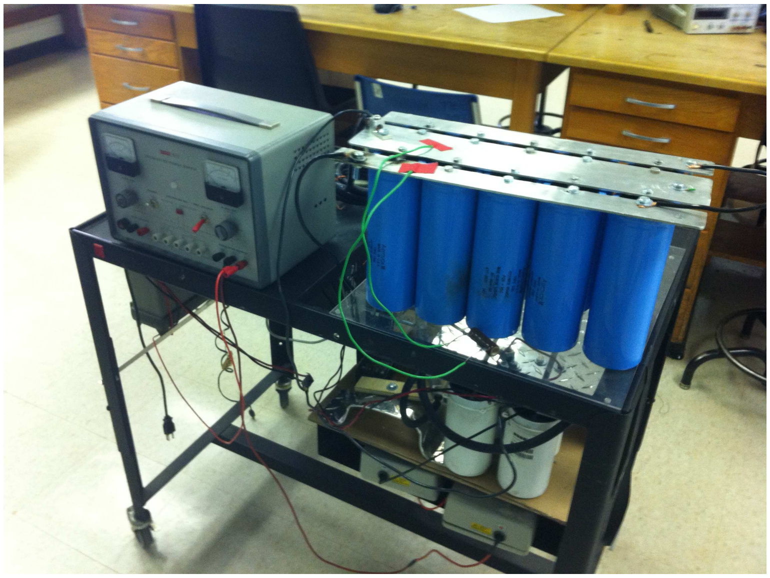

Figure 4: Prototype of EM can crusher

- What components do you think should be added to the existing content?
- How do you consider the theoretical study component?
- How do you consider the computer simulation components?
- How do you think the instructor should do the help you more in the course?
- Do you think the course to be introduced to a wider audience in engineering technology?
- How many projects do you think would be appropriate in the class?
- Will you suggest any other electromagnetics-related projects to the instructor?
- Which one do you prefer, team project or individual project?
- How will you suggest project-based teaching method to other classes?

Some students' comments are listed below:

- The electromagnetic can crusher, in my opinion, is a perfect project for not only learning the fundamentals of electricity and magnetism, but also applying them systematically to accomplish a physical result... With the electromagnetic can crusher, our group worked to optimally apply concepts and theories such as: Ohm's Law, maximum power transfer, electric potential and Lorentz Force, electromagnetic inductance, and transformer theory.
- The EM can crusher allowed one to better understand the application and theory of EMF. It was exciting seeing using design ideas and creativity to put the project together. Also, it allowed the opportunity to establish a team environment.
- The biggest advantage of this project is being able to see these concepts take form and work as we apply them. This allowed us to troubleshoot any problems and improve on our methods as we worked.

- I think the traditional teaching method is too difficult to understand for engineering technology students, most probably, I will lose interest.

6 Conclusions and Discussions

In our project-based class, each student has taken an active role in the learning process. Compared with traditional classroom teaching method, the project-based method is obviously more appropriate to engineering students. During the process, they learned an important merit of engineering technology students: how to apply the theories into practical applications. They have learned and practiced many hands-on skills, from projects planning, financial analysis, material investigation, parts ordering, to hardware implementation, result analysis, and troubleshooting.

One of the major objective of the class, improve the students' interest in electromagnetics, has also been a great success. Before the end of the semester, the team sent me their future plan stating "recently we have been researching self-made antennas (all different types but mostly surface mount). We want to do an antenna project before the end of the semester. Mr. Adams told us about the network analyzer in the power lab. From the microwave class they have different test antennas that we have been tinkering with. The manual has been handy for us to learn how to work the analyzer. Our goal is to mill a surface mount antenna and test it on the analyzer." One team member has been actively seeking summer research opportunities in electrical engineering, and his goal is to pursue graduate studies possibly in applied electromagnetics.

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Biography

Dr. Zhou received the B. Eng. from the University of Science and Technology of China in 1991; M. Eng. from the National University of Singapore in 1999 and the PhD degree from the University of New Mexico in 2005. All degrees are in Electrical Engineering. From 1991 to 1997, he was an Electrical Engineer in China Research Institute of Radiowave Propagation. He joined the School of Computing, the University of Southern Mississippi in 2005 and now serves as an associate professor. His research interests include electromagnetics, radiowave propagation, high performance computing and numerical analysis. His teaching interests include communications, electromagnetics, antennas and propagation, electric power, and signal processing. He is a senior member of IEEE and a member of ASEE.