Laboratory Exercises as an Assessment Tool in an Upper Division Electromagnetic Fields Class – Lessons Learned

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Abstract

As part of a program wide effort to add computation and experimentation to all of our upper division physics courses, a set of laboratory experiments and computational exercises were developed for a junior / senior level course on electromagnetic field theory. The intent of these exercises was to broaden the students' understanding of the subject matter and build upon existing linkages between theoretical analysis, experimentation, and computation. However, in reality, we found that these exercises proved far more useful in identifying conceptual misunderstandings that did not show up in other assessments. They even identified surprising weaknesses in basic experimental technique.

These exercises required students to first find the potential fields produced by simple electrode geometries analytically using the techniques taught in class, then computationally using relaxation techniques in MATLAB and finally experimentally via a water tank simulation. Once they had validated their simulation approaches, the students were to use the computational and experimental methods to find the potential due to a more complex geometry that they could not compute analytically.

Three difficulties became apparent in this process. First, we learned that even when testing indicated that students were able to solve problems and answer conceptual questions, they might lack the ability to transfer that knowledge to a practical problem. Second, we found that lab skills that students learned in other classes did not transfer to a new class. Third, students' lacked confidence in drawing conclusions about experimental results and wrote conclusions without sufficient reflection.

In this paper, we discuss the experiments and computational problems used, the difficulties encountered by both the students and the instructor and ideas for both improving the exercises and addressing the issues identified.

Introduction

In 2012 our department engaged in an effort to integrate computational and experimental problems into our upper division curriculum in a number of classes that traditionally lack labs and are more analytical in nature[1]. These classes include quantum mechanics, theoretical mechanics and electromagnetics. While the intent was to change courses for physics majors, most of the students in the electromagnetics course are electrical engineering majors at our institution. Therefore, we tried to find computational and experimental problems for that course which would interest the engineering students in the class. Our goal was to find a set of problems that were appropriate to the first semester of our electromagnetism sequence (electro- and magneto-statics) and demonstrated the relative strengths of analytical, computational, and experimental methods for solving field problems. While physics majors typically take this course in their junior year, most electrical engineering students take the class during their senior year, concurrent with senior design.

Exercises

We chose implement this idea by creating a set of exercises leading up to the calculation of the capacitance of a microstrip transmission line. The exercise approached this problem in three steps: first the analysis of the coaxial cable using analytical, experimental and computational approaches, then a parallel plate capacitor, and finally a microstrip. At each step, a relaxation technique would be used to solve Laplace's equation computationally in Matlab and a water tank simulation would be used to collect experimental data. In the case of the coaxial cable, the analytical solution was known and this known solution could be compared to the computational and experimental results to validate them.. In the case of the parallel plate capacitor, we had already looked at the simplified case of the infinite parallel plate capacitor, so we could consider the differences between the real and simplified cases. We do not discuss the case of the microstrip in the first semester of our sequence, so the students would need to be quite confident of their experimental and computational methods before tackling it. Thus the students would have an example of validating a computational technique with known cases and the applying it to an unknown case.

For the computational work, we decided to use MATLAB since all of the students had taken a programming course that included MATLAB at some point in their curriculum. The MATLAB language had also been used in prior physics and engineering classes taken by these students. The plan was that students would be given a sample program implementing a relaxation solver for the coaxial cable geometry with specific inner and outer radii that they would need to modify minimally to match the experimental model for their coax. The students would then need to write their own code for the parallel plate capacitor case and modify that for the case of the microstrip. Sample of all of these programs were written and tested by the instructor before the start of the semester in order to identify any likely sources of confusion or difficulty. Samples of the computational portion of this project can be found on our departmental website at stthomas.edu/physics under curriculum development.

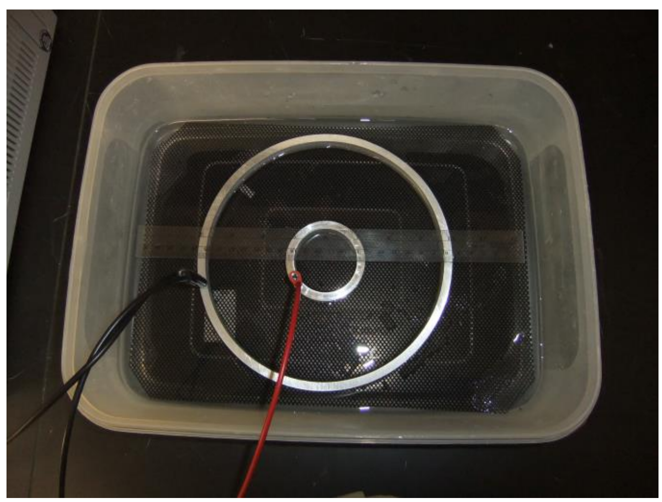

Figure 1 – tank used for experimental portion of exercise

For the experimental part of the exercise, we decided to use the venerable electrolytic tank[2] to simulate electric field measurements in a dielectric. Prior to readily available computational tools, this approach was used to find equipotential surfaces for complex electrode shapes and it has been well characterized over the years[3]. For the purpose of this exercise we fabricated a set of aluminum electrodes for each of the three geometries and used a plastic tank filled with tap water. For ease of measurement, we provided a plastic mesh at the bottom of our water tanks so that students could easily hold their electrical probes in fixed locations as seen in figure 1. While alternating currents are used in water simulation tanks to avoid electrolysis at the surface of the electrodes[4], the low conductivity of tap water meant that as long as we only used voltage measurements in the water (not on the electrodes) we could ignore this effect. We felt that direct current measurements would be easier for students to connect to computation and analytical results. Testing done over the summer before we used these experiments for the first time showed that this apparatus (figure 2) was easy to use and produced excellent results and an excellent match between computational, analytical and experimental results.

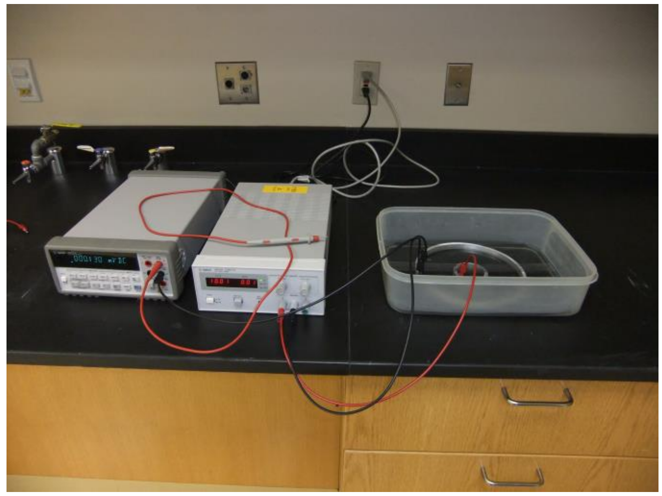

Figure 2 – Complete experimental setup for first portion of exercise

The assignments were divided into three distinct parts. In the first assignment, students would use computation and experiment to find the capacitance of the coaxial geometry and compare their results to known analytical results in order to validate their methods. In the second assignment, through computational determination of the capacitance of the parallel plate capacitor, students would see the limitations of simplifying assumptions used in analytical approaches. Finally the calculation of the capacitance of the microstrip would give the students the opportunity to apply their computational skills to solve a new problem. Since the first exercise was conceptually simple (i.e. slight modifications of an existing simulation program, and simple data collection) the instructions for this portion were minimal, based on the assumption that students would remember concepts and skills from pre-requisite classes. This gave us a chance to use the first assignment to assess transfer of these skills from earlier classes[5].

Classroom Observations

A number of surprises during the first part of this classroom experiment resulted in the later portions being suspended so that we could provide remedial instruction based on problems that became apparent. These problems included surprising difficulties with basic electrical and mechanical measurements and difficulties in presenting and analyzing results. These included:

- Several electrical engineering students had difficulty making or recording radial position measurements. Some observed problems were confusion between diameter and radius, English and metric units, and difficulty finding the center of a circle..
- Some students failed to modify existing Matlab code to match the measured geometry of their experimental apparatus (e.g. using correct inner and outer radii). It was not clear

whether this was due to a lack of familiarity with the programming language or a failure to recognize that the experimental geometry did not match that of the sample program.
- Several electrical engineering students made wiring mistakes when connecting a power supply and voltmeter to the electrodes in the tank.

Clearly, these are skills the electrical engineering students should have mastered in previous coursework. Discussions with students revealed that lack of transfer occurred because they weren't thinking about the need to apply what they had previously learned[6]. In this sense, this turned out to be an important exercise in reminding the students that they are expected to apply what they've learned.

A second interesting observation occurred when some students decided to "improve" the experiment by increasing the current in the electrolytic tank by adding salt. Unfortunately, the choice of using direct current to simplify the conceptual link between measurement and theory made the system behavior extremely sensitive to this change. As a result of this change, the voltage decreased linearly with radius rather than logarithmically (this phenomenon is discussed in detail below). This deviation from the expected behavior was surprising and some students who reported it pointed out that it was not compatible with theory. However, other students plotted the theoretical and experimental results and claimed that they matched in spite of obvious differences in the plots.

Discussing these problems with the students involved, we were able to correct some misunderstandings but it also became apparent that the students were not grasping that the use of the scientific method is critical for engineers. Rather than trying to understand the observed experimental and computational data, they saw these experiments as homework assignments that needed to be completed. Several students cited an increased workload in their senior design class as a contributing factor. Our conclusion was that these activities need to be reinforced in earlier coursework and the exercises in this class function well as an assessment of the student's ability to apply these skills.

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Explanation of Observed Behavior

While we were surprised by the results observed in the classroom, we were even more surprised by the effect of increased conductivity on the experimental results. Since the ac voltages normally used in electrolytic tanks avoid these phenomena they are not described in the literature. However, chemists studying electrochemistry have examined the behavior of ions in solution in electrolytic tanks as well as the reactions that take place at the electrodes[7]. Also material scientists (particularly those interested in naval architecture) have examined the properties of metal immersed in saltwater. Using these results, we were able to determine the electrical, chemical, and material phenomena that gave rise to the observed behavior.

Salt added to the water in the measurement tank quickly dissociates into Na^+ and Cl^- ions. The presence of these free charge carriers dramatically increases the conductivity of the solution. However, for current to flow, electrons must transfer from the negative electrode into the solution and from the solution to the positive electrode. This means that oxidation and reduction reactions must occur at these electrodes. While many reactions are possible at the electrode, the ion concentrations and available electric potential will determine the relative rates of the reactions. For the voltages applied in our experiment, the most significant reactions are those involving the dissociation of water molecules:

$$2H_2O + 2\,e^- \leftrightarrow H_2\,(gas) + 2OH^-$$
$$2H_2O \leftrightarrow O_2(gas) + 4H^+ + 4e^-$$

The bubbling resulting from the development of gas at the electrodes was observed by students but they didn't mention it in their lab reports. Other reactions also occur including the production of a flocculent $Al(OH)_3$ precipitate at the positive electrode.

While the Na^+ and Cl^- ions are fairly uniformly distributed throughout the solution at the beginning of the experiment, the H^+ and OH^- ions produced at the electrodes are most highly concentrated near the electrodes and diffuse from there into the bulk of the solution where they recombine in order to maintain equilibrium ($[H^+][OH^-] = 10^{-14}$ $[H_2O]$).This means that rather than an electrical current in the solution that is constant at all radii (giving a current density inversely proportional to radius), we find that the conductivity varies with radius as ion density varies. We were able to use indicator dyes to verify the extreme acidity and alkalinity of the solution near the electrodes as shown in figure 3.

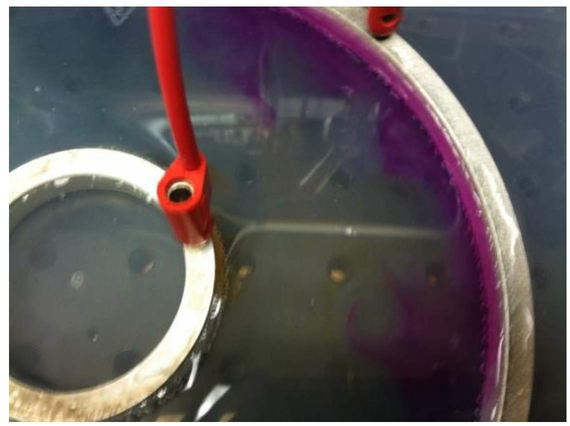

Figure 3 - Use of indicator dye to detect spatial variations of charge carriers

While this explained the non-logarithmic voltage plots, it did not explain why the phenomenon persisted when the salt water was replaced with tap water. For this we need to understand the material properties of the aluminum electrodes. Aluminum is a very reactive metal which is normally passivated by a thin layer of Aluminum oxide which forms naturally on the surface of aluminum exposed to air. This oxide layer is quite hard and corrosion resistant. However, it is soluble in either extremely acidic or extremely alkaline solutions. Because of the production of hydrogen and hydroxyl ions at the electrodes, the solution near the positive and negative electrodes becomes acidic and alkaline

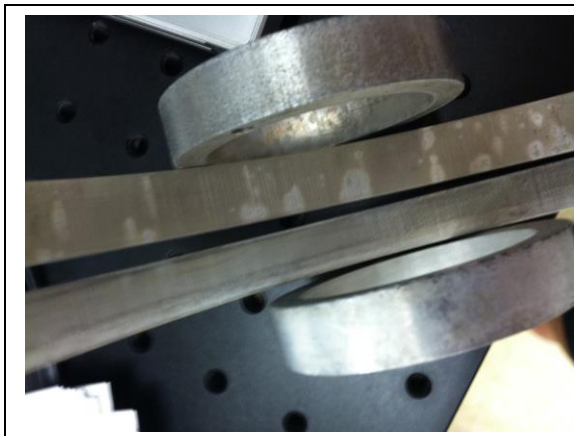

Figure 4 – Aluminum electrodes after use in salt water

respectively. In this environment, the protective oxide layer dissolves, exposing the reactive aluminum beneath. Material scientists have found that under these conditions, aluminum preferentially erodes along grain boundaries. In some cases, this gives rise to hollow pockets hidden beneath a porous surface. Close examination of the electrodes after use in saltwater reveals that surfaces exposed to acidic and alkaline regions are indeed pockmarked and discolored, while areas exposed only to neutral solutions remained pristine (figure 4). It is our belief that these pockets and pores provide hiding places for salt even after normal cleaning, which would explain why contaminated electrodes continue to exhibit peculiar behavior even after washing. To test this, we attempted to clean these pores by immersion in vinegar. We found that this indeed eliminated the effect of the salt water although we don't believe this result is conclusive.

Conclusions and Next Steps

While this exercise did not work as originally expected, its detection of weaknesses the general problem solving abilities of our engineering students was invaluable. While the original purposes of the lab exercise might be better served via a more traditional excitation via ac voltages, it is not clear that this will be as good a tool for detecting how students respond to differences between experimental and theoretical results. Further analysis of the detailed ionic behavior in the tank with dc excitation is worth pursuing but is not directly relevant to the electromagnetic fields class for electrical engineers. Our plan is to use ac excitation for class and attempt to identify problems elsewhere. We will continue to use these exercises to provide assessment feedback to electrical engineering faculty.

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