# ON THE USAGE AND POTENTIAL APPLICATIONS OF THE FINITE ELEMENT METHOD MAGNETICS (FEMM) PACKAGE IN THE TEACHING OF ELECTROMAGNETICS IN HIGHER EDUCATION

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ABSTRACT
Finite Element Method Magnetics (FEMM) is an open source finite element analysis software package for solving 2D planar and 3D axisymmetric low frequency electromagnetic problems including both electrostatics and magnetostatics. The program addresses linear and nonlinear harmonic magnetic and magnetostatic problems and linear electrostatic problems. It is a simple, accurate, and low computational cost freeware product, popular in science and engineering. Several applications in areas such as electromagnetics, materials science, industry, medicine, experimental and particle physics, robotics, astronomy and space engineering can be found. However its educational value has been underestimated. Use of the package in education is quite rare. The aim of this paper is to explore the capability of FEMM to meet as a complementary tool the needs of teaching electromagnetics in higher education. In order to demonstrate its use and exhibit the aid it offers in the teaching of electromagnetics illustrative examples are given. To evaluate its effect in the learning process a study with three groups of students has taken place. The students of the first group have not used the software; second group students have practiced in the computers lab while the rest have installed it in their home computers and pursued short independent projects. Study of the statistics of the students' grades distribution is made. Performance of the third group students is significantly better, showing that the free distribution of FEMM is one of its major advantages. A questionnaire about the use of educational software has been also given in the students in the start of the course and after the examinations. Interesting conclusions have been derived and presented here.

KEYWORDS
Education, software tools, learning preferences, modeling, finite element analysis, electromagnetics.

## INTRODUCTION

The finite element method (FEM) is a numerical procedure that can be applied to obtain solutions to a variety of problems in engineering and science. Steady, transient, linear and nonlinear problems in electromagnetics, structural analysis, and fluid dynamics may be analyzed and solved with it, (Volakis et al., 1998; Moaveni, 1999). In 1943, Courant has been the first person developed the method, (Courant, 1943). Its main advantage is its capability to treat any type of geometry and material inhomogeneity without a need to alter the formulation of the computer code that implements it providing geometrical fidelity and unrestricted material treatment. The idea of the method is to break the problem down into a large number of regions, each with a simple geometry. As a result, the domain breaks down into a number of small elements and the problem is transformed from a small but difficult to solve one into a big but relatively easy to solve. Through the process of discretization, a linear algebra problem is formed with many unknowns. However, algorithms exist that allow the resulting linear algebra problem to be solved, usually in a short amount of time.

In the case of electromagnetics it is well known that a discretization scheme, such as the one that FEM implies, which implicitly incorporate most of the theoretical features of the problem under analysis is the best solution to get accurate results. It is a very often used method efficient for modeling various physical problems, e.g. electrostatics, magnetostatics, magnetodynamics, etc. with complex geometries, nonlinearities, etc. Although the differential equations of interest, (e.g. Harrington, 1961), appear relatively compact, it is very difficult to get closed–form solutions for all but the simplest geometries. This is where finite elements method comes in.

Finite Element Method Magnetics (FEMM) software has been developed for this reason addressing some limiting cases of Maxwell's equations. The magnetic problems addressed are those that can be considered as low frequency problems in which displacement currents can be ignored. In a similar vein, the electrostatics solver considers the converse case in which only the electric field is considered while the magnetic field is neglected. The program addresses 2D planar and 3D axisymmetric linear and nonlinear harmonic magnetic, magnetostatic and linear electrostatic problems, (Meeker, 2004).

FEMM package is an open source, simple, accurate, and low computational cost freeware product, popular in science and engineering. Several applications in areas such as electromagnetics, (Íñiquez et al., 2005), materials science, (Pamme, 2006), industry, (Wichert and Kub, 2005), medicine, (Rotariu et al., 2005), experimental and particle physics, (Lee et al., 2006; Picker, 2004), robotics, (Zandsteeg, 2005), astronomy, (Acuña et al., 2002), and space engineering, (Boniface et al., 2005), can be found. However its educational value has not been credited. The physics and engineering introductory courses in electromagnetics have remained traditional in many ways during the years. Unfortunately a software tool is rarely used in such a course for lots of reasons. Commercial software, (e.g. FEKO, (http://www.feko.info), and SEMCAD X, (http://www.speag.com)), is reliable and fast. However students following a course in a university or a technological institute are not likely to take an in–depth electromagnetics course that would entail sophisticated simulations requiring such tools. The high performance simulations available in commercial packages remain out of reach. Other suggestions, (e.g. Dular et al., 1999), do not meet the criteria for the average PC user. However it would be beneficial for students to use a software tool. FEMM package comes to meet these needs.

In this paper it will be shown that FEMM is a software tool that may help students in an undergraduate course to understand electromagnetics much better. The software is reasonably fast and accurate, user friendly and freely distributed. Its capability to meet as a complementary tool the needs of teaching electromagnetics in higher education will be explored and evaluated.

The paper is organized as follows. In the beginning some discussion of electromagnetics and FEM basic principles is made. Then the main characteristics of FEMM are presented. In order to point out the evolutionary features of the software environment a sequence of stages of teaching accompanying with an illustrative example follows. The formal evaluation of the effectiveness of the package as an educational tool, based on the students' grades distribution, is presented afterwards. In an effort to assess the students' perception of using educational software survey data are also given. The paper ends with some comments and conclusions.

## THEORETICAL BACKGROUND

The FEMM package addresses some limiting cases of Maxwell's equations, (Harrington, 1961), the magnetostatics, electrostatics, and the low–frequency time–harmonic magnetic problems. In the first two cases problems fields are time–invariant and Maxwell's equations become:

$$\nabla \cdot \mathbf{E} = \rho/\varepsilon \quad (1) \qquad \nabla \times \mathbf{E} = 0 \quad (2)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (3) \qquad \nabla \times \mathbf{B} = \mu \mathbf{J} \quad (4)$$

where $\mathbf{E}$ the electric field intensity, $\mathbf{B}$ the magnetic field flux density, $\mathbf{J}$ the current density, $\rho$ the charge density, $\varepsilon$ the electrical permittivity, and $\mu$ the magnetic permeability. Quantities $\mathbf{E}$ and $\mathbf{J}$ obey the constitutive relationship:

$$\mathbf{J} = \sigma \mathbf{E} \quad (5)$$

where $\sigma$ stands for conductivity of the medium.

In the case of a magnetostatic problem FEMM goes about finding a field that satisfies (3)-(4) via a magnetic vector potential approach, (Meeker, 2004),. Flux density is written in terms of the vector potential $\mathbf{A}$, as:

$$\mathbf{B} = \nabla \times \mathbf{A} \tag{6}$$

Then Eq. (4) becomes:

$$\nabla \times \left( \frac{1}{\mu(\mathbf{B})} \nabla \times \mathbf{A} \right) = \mathbf{J} \tag{7}$$

In an electrostatic problem FEMM employs the electric scalar potential $V$, defined from the expression

$$\mathbf{E} = -\nabla V \tag{8}$$

The differential equation solved by FEMM is:

$$-\varepsilon \nabla^2 V = \rho \tag{9}$$

Low–frequency time–harmonic magnetic problems for the case in which the filed is oscillating in one fixed frequency $\omega$, can also be solved with FEMM. In this case it is shown, (Meeker, 2004), that the equation that FEMM actually solves is the

$$\nabla \times \left( \frac{1}{\mu_{eff}(\mathbf{B})} \nabla \times \boldsymbol{\alpha} \right) = -j\omega\sigma\boldsymbol{\alpha} + \hat{\mathbf{J}}_{\mathbf{src}} - \sigma \nabla V \tag{10}$$

where $\hat{\mathbf{J}}_{\mathbf{src}}$ the phasor transform of the applied current sources, $\mu_{eff}(\mathbf{B})$ the effective magnetic permeability selected to give the correct amplitude of the waveform under sinusoidal excitation, while $\boldsymbol{\alpha}$ is the amplitude of the phasor transformation, (Hoole, 1989), of $\mathbf{A}$, defined from the expression:

$$\mathbf{A} = \operatorname{Re}\left\{ \boldsymbol{\alpha} \left( \cos \omega t + j \sin \omega t \right) \right\} = \operatorname{Re}\left\{ \boldsymbol{\alpha} e^{jwt} \right\} \tag{11}$$

Last but not least the boundary conditions, (Harrington, 1961), needed to guarantee a unique solution for FEMM are, (Meeker, 2004):

- The Dirichlet boundary condition: The value of potential is explicitly defined on the boundary, (e.g. $\mathbf{A} = 0$).
- The Neumann boundary condition: The normal derivative of potential is specified along the boundary, (e.g. $\frac{\partial \mathbf{A}}{\partial \hat{\mathbf{n}}} = 0$).
- The Robin boundary condition: This is a mix of the previous two conditions, (e.g. $\frac{\partial \mathbf{A}}{\partial \hat{\mathbf{n}}} + c\mathbf{A} = 0$).

As it has already been said the finite element method is applied in many fields of computer aided engineering and used for obtaining approximate solutions to the partial differential equations must be solved. The basic concept of the method is that although the behavior of a function may be complex when viewed over a large region, a simple approximation may be sufficed for a small subregion. Its idea is derived from the difficulty to get closed–form solutions for all but the simplest geometries, even though the differential equations of interest appear relatively compact. In practice, it utilizes a variational problem that involves an integral of the differential equation over the problem domain. This domain is divided into a large number of non–overlapping subregions, called finite elements, each with a simple geometry (e.g. triangles). Over each subregion the solution of the partial differential equation is approximated by a simple polynomial function. These polynomials have to be pieced together so that where the edges of adjoining elements overlap the field representations must agree to maintain continuity of the field. Once this has been done, the variational integral is evaluated as a sum of contributions from each finite element. The result is an algebraic system for the approximate solution having a finite size than the original infinite–dimensional partial differential equation. If enough small regions are used, the approximate potential closely matches the exact solution. The advantage of breaking the domain down into a number of small elements is the problem transformation from a small but difficult to solve into a big but relatively easy to solve one. The main characteristic of the method is the partial differential equation discretization with the approximate solution known throughout the domain as a pieceise function and not just as a set of points unlike other computational methods.

In brief the steps involved in the generation and solution of a FEM system are:

I. Definition of the problem's computational domain.
II. Mesh truncation schemes choice.
III. Discrete elements and shape functions choice.
IV. Mesh generation.
V. Wave equation enforcement over each element in order to generate the element matrices.
VI. Boundary conditions application and element matrices assembly for the formation of the over–all system.
VII. Matrix symmetry ensuring.
VIII. Solver choice.
IX. Matrix system solution.
X. Field data postprocessing and extraction of parameters of interesting.

## THE MAIN CHARACTERISTICS OF FEMM PACKAGE

FEMM is a suite of programs for solving low frequency electromagnetic problems on two–dimensional planar and axisymmetric domains. The program addresses both linear and nonlinear magnetostatic and time harmonic magnetic problems as well as linear electrostatic ones. Its main advantages are:

1. It is freeware.
2. It has a user friendly interface.
3. It is easy to learn.
4. Users' contributions libraries provide support and applications.
5. Its computational cost is low.
6. Comparisons with commercial software have shown its reliability.
7. The Lua extension language, (Ierusalimschy, 2006), used to add scripting/batch processing facilities to FEMM is an open–source code.

For a professional engineer advantages (5)-(7) are important. However, when we focus in the choice of an educational software, the advantages (1)-(4) are the most significant.

FEMM is divided into three parts, (Meeker, 2004): The interactive shell (femm.exe), which is a multiple document interface pre-processor and a post-processor for the various types of problems solved by FEMM; the triangle.exe program, its feature is the segmentation of the solution region into a large number of triangles; the solvers (fkern.exe for magnetics and belasolv for electrostatics). Each solver takes a set of data files that describe problem and solves Maxwell's equations to obtain values for the desired field throughout the solution domain. Concerning the application of finite element method FEMM divides the solution region into triangles. The value of potential in each triangle is approximated from the linear interpolation of its values at the three vertices of the triangle.

For additional information a visit in the package webpage, (http://femm.foster-miller.net), is suggested. There software downloads, answers to FAQ, manuals, tutorials, examples, etc. can be found.

## EDUCATIONAL USE OF FEMM: A TYPICAL EXAMPLE

A modern pedagogical proposal should be based, (Vallim et al., 2006), on three concepts:

A. "New Learning is Based on Previous Learning", (Piaget, 1975)
B. "Learning is Social and Personal Process", (Vygotsky, 1978)
C. "Context Helps Motivate Learning", (Papert, 1978)

One point arises as we consider the consistency between the above concepts and the use of FEMM as a teaching tool. The students' previous conceptions play an important role in their learning. A previous module in which specific computer skills are taught and a prior knowledge of the basic principles of electromagnetics satisfy concept A. Personal effort is an essential component of learning. However, social interaction allows students to act as mediators of knowledge for each other. Students working in a group can solve problems that they would not be able to solve alone. At the same time, they share knowledge and strategies of solution that foster individual learning. The idea of working in groups of two people is quite common and gives good results, (Roberts, 2005). The motivation of students is increased when the learning environment creates a suitable context for a personal experience in the building of knowledge. Including computer modeling and simulations in a theoretical course acts definitely as a motive force, (Gorman et al. (ed.), 2005).

To demonstrate the application of FEMM as an educational material a step–by–step process to analyze a specific magnetic problem, quite common in the curriculum of a course in electromagnetics, is presented:

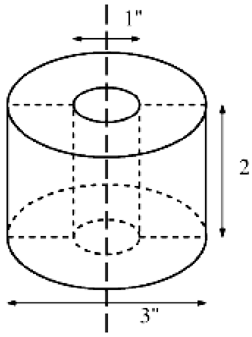

Figure 1. Air–cored coil geometry.

- STEP 1: SYSTEM DESCRIPTION. An air–cored solenoid in open space, see Figure 1, is considered. The coil has an inner diameter of 1 inch, an outer diameter of 3 inches, and an axial length of 2 inches. The coil is built out of 1000 turns of 18 AWG copper wire. A steady current of 1A is flowing through the wire.
- STEP 2: MODEL ANALYSIS. The problem is a magnetostatic, axisymmetric one. We set inches as measurement unit. Grid Size is taken equal to 0.5. A discussion in the computers lab may take place. Students can be asked for the reasons of the above statements and choices.
- STEP 3: MODEL'S BOUNDARIES DEFINITION. The key to using the preprocessor is that it is always in one of five modes: the Point, the Segment, the Arc Segment, the Block, or the Group mode. First four correspond to the four types of entities that define the problems geometry: nodes that define all corners in the solution geometry, line segments and arc segments connecting the nodes to form boundaries and interfaces, and block labels that denote the material properties and mesh size associated with each solution region. When the preprocessor is in one of these drawing modes, editing operations take place only upon the selected type of entity. The fifth mode, the group mode, is meant to glue different objects together into parts so that entire parts can be manipulated more easily. The first task is to draw boundaries for the solution region. It is necessary for students to understand the model geometry. In our case the field of interest is vertical to the symmetry axis. Design of a box with dimensions 2 and 4 Grid steps and a hemisphere that encloses it, see Figure 2, is enough.
- STEP 4: MATERIALS DESCRIPTION. To make a solvable problem definition, the user must identify block materials properties. FEMM has a built–in library that allows a variety of materials such as the air, PM materials, soft magnetic materials, solid non–magnetic conductors, and Copper SWG, AWG, and metric, magnet wires. For each material a number of different options are available. Materials from other libraries or models can also be imported and used. In the current example the coil is made from copper AWG 18, a linear magnetic material with null hysteresis lag angles and equal relative permeability in the $z-$ and $r-$ main axes, see Figure 3. However this feature interests more professionals. Students in an undergraduate level are not likely to take an in–depth electromagnetics course that would entail sophisticated simulations and advanced materials requiring taking advance of such a feature.
- STEP 5: BOUNDARY CONDITIONS DESCRIPTION. Specification of the properties of line segments or arc segments that are to be boundaries of the solution domain is the last but not least step in the system modeling. All the boundary conditions mentioned earlier are allowed. A thorough analysis of this subject is probably out of the needs of an undergraduate student.
- STEP 6: MESS GENERATION. The next step is the discretization of the solution space. FEMM breaks the problem down into a large number of triangles, see Figure 4. Different mesh size values can be set in each area allowing an increased accuracy without a similar increase in the computational cost.
- STEP 7: RUN FINITE ELEMENT METHOD. Main menu option Analysis>Analyzes runs the finite element method. The time required for the simulation is highly dependent on the problem being solved. Solution times can range from less than a second to several hours, depending upon the size and complexity of the problem. Generally, linear magnetostatic problems take the least amount of time. Harmonic problems take slightly more time, because the answer is in terms of complex numbers. The slowest problems to analyze are nonlinear time-harmonic, since multiple successive approximation iterations must be used to converge on the final solution. However, nonlinear problems take a few

iterations. In these problems later iterations usually are quite fast compared to the first two iterations because they can be initialized with an approximate solution that is very close to the "actual" solution.

- STEP 8: ANALYSIS RESULTS. Numerous presentations are possible: Flux and current density plots, see Figures 5-6, contour plots of flux lines, see Figure 7, and vector plots of the magnetic field flux density and intensity, see Figures 8-9, are provided. Other analysis options are the calculation of line integrals along a specified contour line and the calculation of volume integrals over a specified volume defined from a specified closed contour line. Both kinds of integrals can be calculated for a series of quantities, (Meeker, 2004). Such calculations are very useful in the learning procedure. Students can be asked to make comparisons between numerical results and theory.

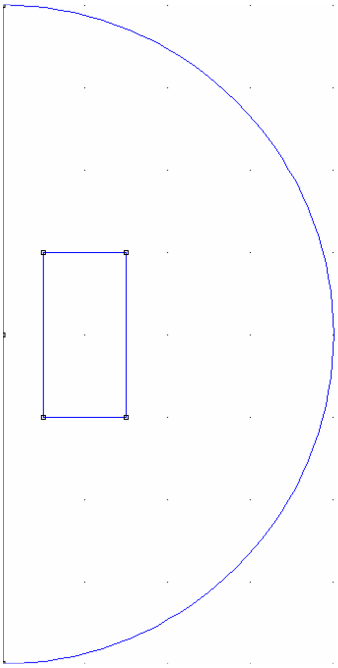

Figure 2. Model Geometry.

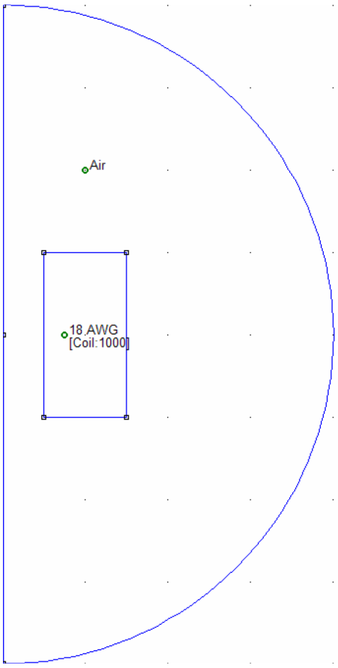

Figure 3. Proposed model.

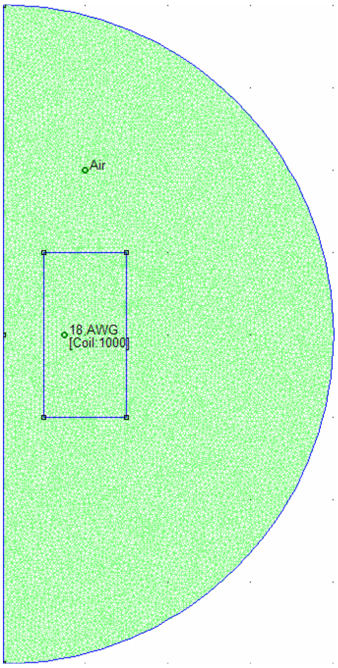

Figure 4. Mesh generation.

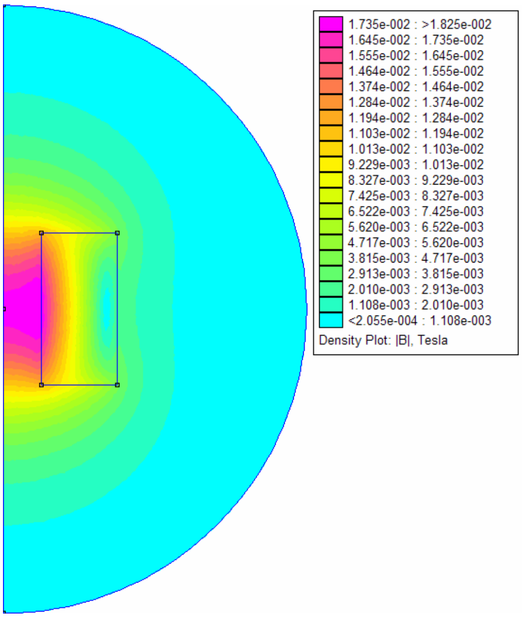

Figure 5. Flux density plot.

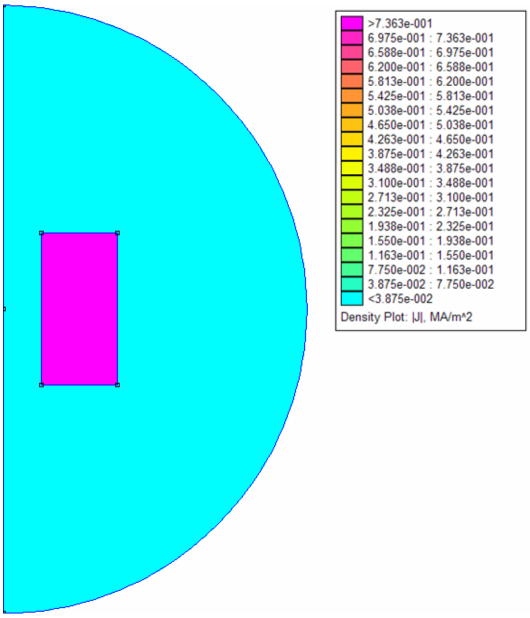

Figure 6. Current density plot.

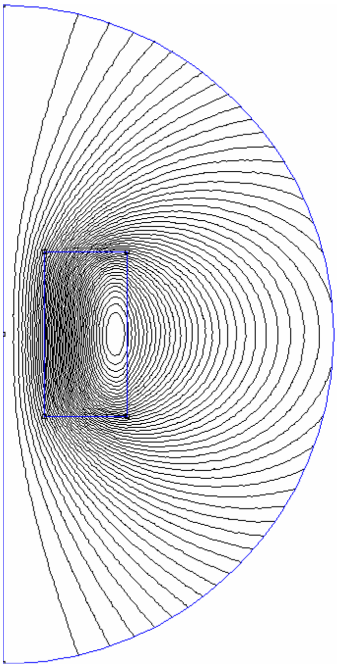

Figure 7. Flux lines contour plot.

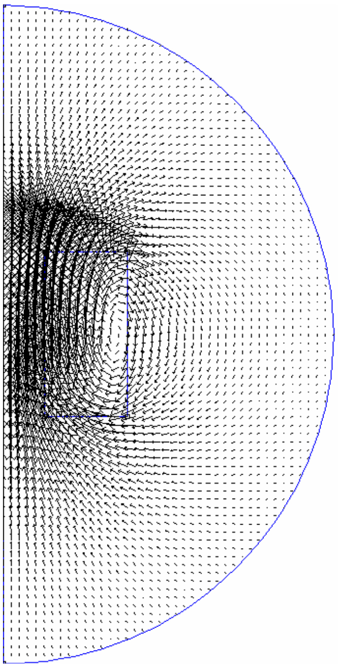

Figure 8. Magnetic field flux density vector plot.

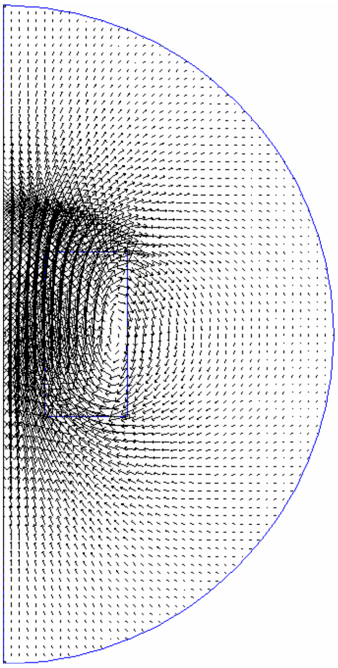

Figure 9. Magnetic field intensity vector plot.

In the case of time harmonic magnetic problems additional information, concerning both real and imaginary parts of the quantities calculated, can be gathered. The main difference is that not only real but also imaginary quantities can be calculated and illustrated. No significant differences when electrostatic problems are simulated exist. In this case electrical instead of magnetic quantities are calculated and illustrated. For more information see the electrostatics tutorial of FEMM 4.0, (Meeker, 2004).

FEMM software and its applications can be evolutive in the sense that the offered tools are of various levels of complexity. A student can tackle, step by step, depending on his apprenticeship level, various tools adapted to the solving of problems of increasing complexity. Through this simple example the evolutionary characteristics the specific software has as an educational tool become apparent.

## EVALUATION (I): ACADEMIC RESULTS

In past years, there was a debate over whether evaluations should be based on qualitative or quantitative data. Qualitative proponents argued that thick descriptions and particular knowledge gained from program participants outweighed quantitative indicators like test scores. Quantitative proponents argued that test scores and other numerical findings provided more objective evidence of the effects of programs. This debate has been resolved by both sides recognizing the place of both quantitative and qualitative data and that the best studies would incorporate both kinds, (deMarrais et al., (eds.), 2004). Considering that student performance is one of the most widely used quality metrics when evaluating a curriculum, a pedagogical approach or a learning preference, (Macías–Guarasa et al., 2006), undergraduate student's grades have been monitoring to evaluate their degree of achievement of the application of FEMM software in the teaching of electromagnetics. As the detailed evaluation criteria are closely related to the measurement of the fulfilment of the course objectives, the higher the grades, the higher the degree of achievement.

To evaluate the effectiveness of the FEMM in the learning process, 266 students at the fourth semester of their studies in Physics have been considered. Three groups have been formed. Students of group A have not used FEMM; group B students have performed simulations in the computers lab; the rest, group C, have installed the package in their home computers and prepared independent short projects.

Students were randomly assigned into the groups. A study of the students' grades distribution in the final exams in the course of electromagnetics has been made. Data in Table 1 offer an analytical view of the students' final exams results, (score between 0 and 10). In Figure 10 the final exams grading histogram is given.

Table 1. Final Exams Results

Final Exams Results

| Grade | | Number of Students | | |
|---|---|---|---|---|
| | | Group A ($n=87$) | Group B ($n=90$) | Group C ($n=89$) |
| 0 | Fail | 10 | 7 | 8 |
| 1 | | 15 | 12 | 13 |
| 2 | | 17 | 23 | 15 |
| 3 | | 10 | 10 | 6 |
| 4 | | 8 | 7 | 8 |
| 5 | Pass | 9 | 7 | 8 |
| 6 | | 4 | 7 | 7 |
| 7 | Good | 7 | 4 | 9 |
| 8 | | 3 | 7 | 7 |
| 9 | Very Good | 2 | 3 | 5 |
| 10 | | 2 | 3 | 3 |

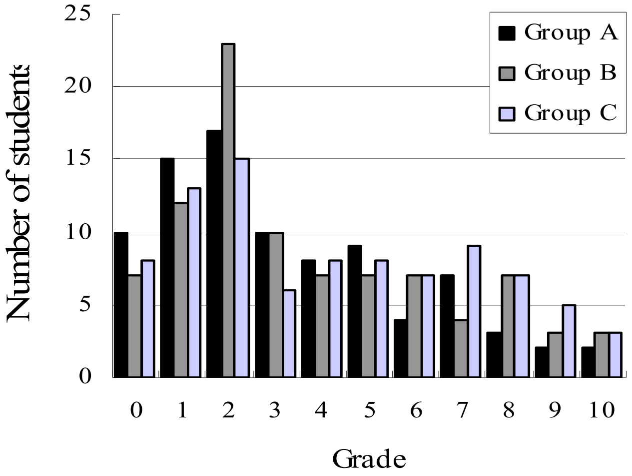

Figure 10. Final exams grading histogram.

It easily comes that students who have used FEMM software as a complementary educational tool (groups B and C) have obtained better academic results. The greater improvement has shown the students of group C. An explanation for this outcome might be the student's behaviour and attitude towards teamwork and collaborative production. Similar results are obtained from Figures 11 and 12. In Figure 11 the ratio of the students who have passed the final exams to the ones who have failed is illustrated, validating the statements previously made. In Figure 12 the accumulative grading distribution of the students who have passed the course is presented. In this case no significant difference exists. From the above we conclude that the usage of FEMM as a complementary tool in teaching electromagnetics is helpful for the students, however further investigation is needed due to the large number of students who have not passed the exams, (only 33% of the total number have passed). Surprisingly a bit, improvement is better for these students who worked independently at their homes rather collaboratively in a computer lab. Because of the limited number of students and some correlations that are not very significant, the last result must be taken with caution. If this is a case the free distribution character of the FEMM package is a further significant advantage of the software.

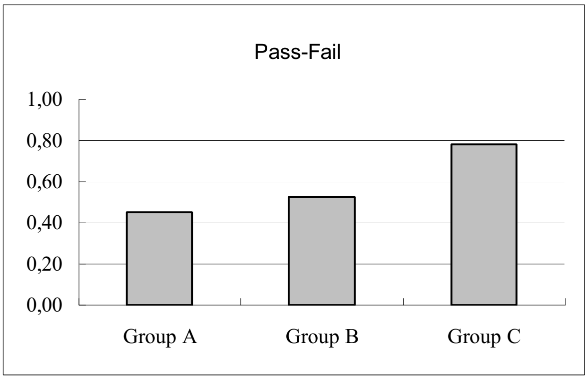

Figure 11. Ratio of students who have passed the exams to the ones who have failed.

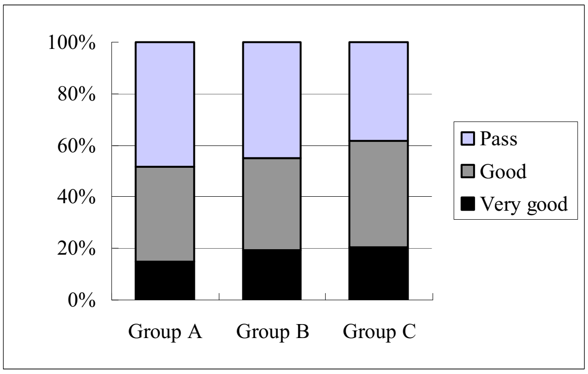

Figure 12. Normalized grades distribution of students who have passed the exams.

## EVALUATION (II): STUDENT SURVEYS

When adopting the use of FEMM software as a complementary educational tool a quality metrics related to the student's perspective using student surveys has been done. In the evaluation shown below, among all the possible performance measured metrics, these that stand out as the most appropriate ones, linked to the following statements presented to the students. Two anonymous surveys have been done. In the first at the beginning of the semester all the students have participated. In this survey it was not known in which of the three groups students would participate. In the second one, that has taken place after the final exams, only students of groups B and C have participated. Unfortunately we could not know their particular responses in the first survey. However large survey population and the fact that groups were randomly formed allow us to assume that results presented in Figure 13 illustrate not only total but each group opinions independently.

First survey questions:
- [Q1.1] The use of FEMM package can increase my affinity to electromagnetics.
- [Q1.2] The use of FEMM package could help me to improve my academic results.
- [Q1.3] The use of FEMM package would be interesting.
- [Q1.4] I would like to use a software package in the teaching of electromagnetics.

Second survey questions:
- [Q2.1] The use of FEMM package has increased my affinity to electromagnetics.
- [Q2.2] The use of FEMM package has helped me to improve my academic results.
- [Q2.3] The use of FEMM package has been interesting.
- [Q2.4] The effort imposed by the use of FEMM package is worthwhile because of abilities and knowledge acquired.

To answer the questions, students had to choose between five different answers with a numerical value: Fully Agree (5); Agree (4); Partially Agree (3); Partially Disagree; (2); Disagree (1); Fully Disagree (0).

In the first survey, see Figure 13, regarding the increase in their affinity to electromagnetics, [Q1.1], students show a positive tendency, averaging 2.60. They believed that it could help them to improve their academic records, [Q1.2], giving it an average value of 2.65. However a few only believed that package's use could be interesting, [Q1.3], averaging 2.16. The minority of the students were also prejudiced against the use of the software giving an average value of 1.85 in [Q1.4]. The percentage of the positive answers, i.e. at least partially agree, are correspondingly 54%, 56%, 44%, and 35%. It has to be noticed that even though students found advantages in the use of the package, the majority did not want to use it!

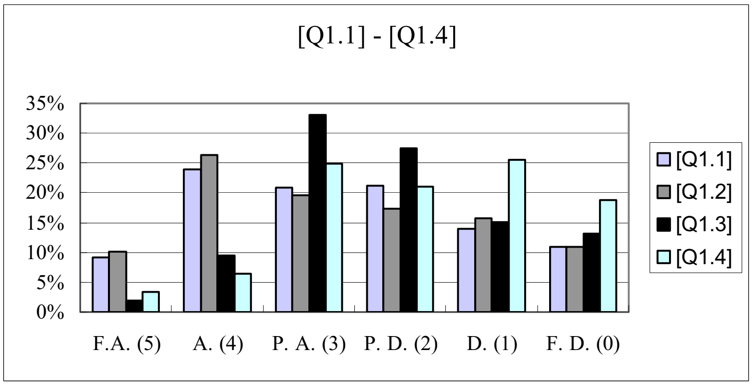

Figure 13. First survey results.

Results of the second survey are illustrated in Figures 14-17. Comparing the two groups, students of group C are expressed more positively in questions [Q2.1] and [Q2.2], while group B students in [Q2.3] and [Q2.4]. Student's performance in the final exams, students of group C have obtained better grades, justifies the results in the first two questions. However the non–positive feelings undergraduate students have sometimes about requisite independent short–projects resulted in their different attitude to the last two questions. Especially in [Q2.4], which is the most important question because it roughly measures the ratio between two perceived variables, learning vs. required effort, results probably do not reflect students' opinions about the question but their dislike for the increased workload. In Table 2 the average values of the opinions of the students in the questions of the second survey are given. Accepting as a safe evaluation criterion the fulfilment of the course objectives directly expressed by the academic results the opinion of students of group C about FEMM looks most promising than the rest.

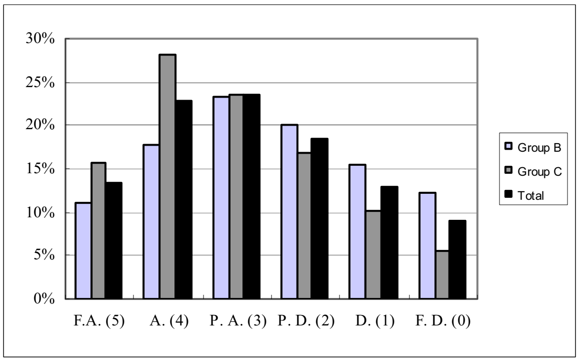

Figure 14. [Q2.1], Increase in affinity to electromagnetics.

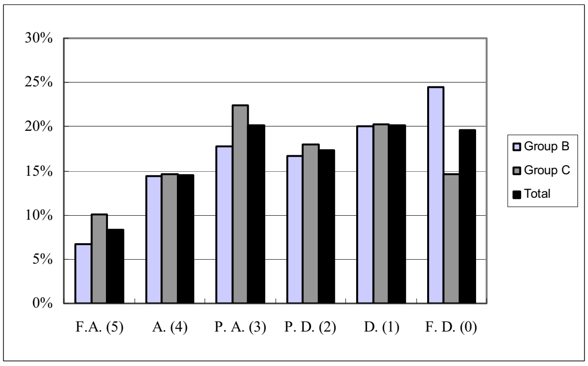

Figure 15. [Q2.2], Academic results improvement.

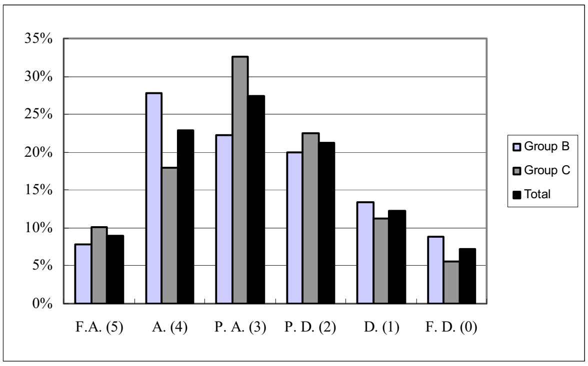

Figure 16. [Q2.3], Software interest.

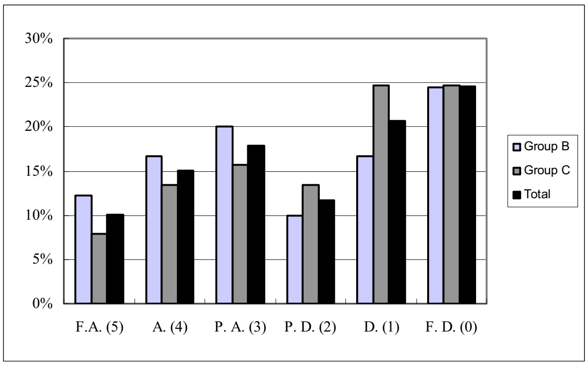

Figure 17. [Q2.4], Effort worth.

Table 2. Second Survey Questions Average Values

| [Q2.1] | | | [Q2.2] | | | [Q2.3] | | | [Q2.4] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| B | C | Total | B | C | Total | B | C | Total | B | C | Total |
| 2.52 | 3.06 | 2.79 | 1.98 | 2.33 | 2.15 | 2.70 | 2.76 | 2.73 | 2.24 | 1.92 | 2.08 |

In Figure 18 the post–test and pre–test students' answers in the corresponding questions of the two surveys are compared. Results are given in terms of the ratio $R_x$, x=1..4, of the number of students who gave for question [Q2.x] a specific answer, (post–test), to the number who gave the same answer for question [Q1.x], (pre–test), normalized to the ratio of total number of answers; i.e. if $X$ the total number of students and $Y$ the population of groups B and C, the ratio found before is divided by $Y/X$. In the main, at the end of the course students have been more positive for FEMM package and its use as a complementary educational tool, with the exception of the answers in the second question, (academic results improvement). Their poor performance in the final exams despite their positive attitude in the beginning of the course may be an explanation for this.

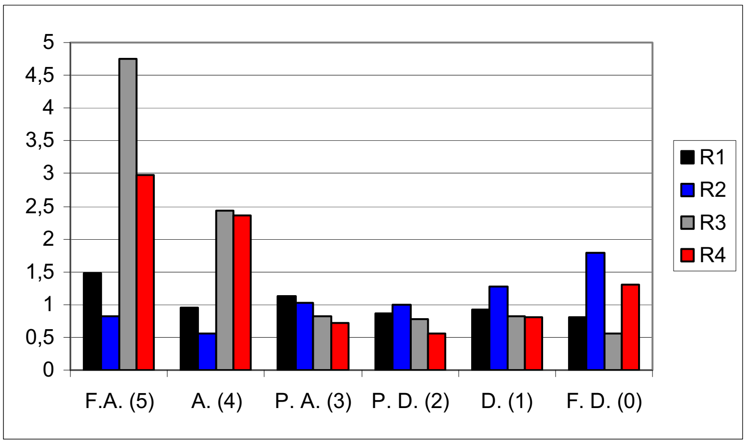

Figure 18. Post–test to pre–test students answers comparison.

## CONCLUSIONS

Finite Element Method Magnetics (FEMM) package is a simple, accurate, and low computational cost freeware tool for performing simulations in electromagnetics. Despite its popularity in science and engineering its educational value has been underestimated. In this paper the capability of FEMM package to meet as a complementary tool the needs of teaching electromagnetics in higher education has been explored. The paper provides a brief overview of the software environment and its potential applications. A demonstration of its features it presented through a simple example. Academic results and students surveys have been used for the evaluation of the effectiveness of the package in the learning process. Students who have used the software show improved academic results, especially the ones who pursued short independent projects. In general students are satisfied with the use of the package although their initial expectations were greater. A framework establishing a basis for comparison of a wider range of cases studies in accordance with students performance may be helpful. Finally, the free distribution of FEMM, from the educator point of view, is one of its major advantages.

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