# AC 2010-821: ENHANCING ELECTROMAGNETICS INSTRUCTION USING MATLAB AND MATHCAD

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# Enhancing Electromagnetics Instruction Using MATLAB and MATHCAD

## Abstract

MATLAB and MATHCAD can be very useful tools for use in electromagnetics courses. They can be used as demonstration tools to clarify important concepts, or for numerical analysis of problems that are difficult or impossible to solve analytically. MATLAB can serve as the students' home laboratory, helping to develop their practical understanding of electromagnetics. MATHCAD, with its symbolic algebra system, is useful for analyzing complicated mathematical expressions and is ideal for subjects that deal with mathematical representations of real or complex functions. Examples show how these tools are used in undergraduate course from three universities.

## Introduction

Electromagnetics in electrical engineering is generally taught as a one or a two semester sequence in the junior year. Also, some computer engineering students will take one semester of electromagnetics to get a better understanding of transmission lines and smart antennas. The trend has been to decrease coverage from the more traditional two semester sequence to a single semester course to make room for other topics. However, a de-emphasis is unfortunate since the subject is fundamental to the understanding of wireless communications, radar systems (such as new airport systems), GPS operation, transportation systems (anti-collision radar, maglev), RFID systems, medical imaging systems (MRI), and bioelectromagnetics.

The universities involved in this paper have different approaches to covering Electromagnetics. One University presently has a two semester sequence of electromagnetics and presently uses the T-Lines first approach. The second university had a three (3) hour junior level course but increased it to four (4) starting in Fall of 2008. The extra credit may be just enough to cover more materials on transmission lines and some additional applications using software packages. The third university also requires a four (4) credit core electromagnetics course that begins with electrostatics and progresses through EM wave propagation and ends with transmission lines. Students can also take senior level classes in antennas, microwave engineering, high speed systems and optical systems.

Electromagnetics can be challenging for students for several reasons. First, fields are vector quantities and students must visualize directions in space. This can be complicated by the necessity of studying different coordinate systems (Cartesian, cylindrical and spherical). Also, students are required to perform integration and differentiation, skills they have somewhat developed but have rarely applied. This paper will describe ways in which MATLAB and MATHCAD are employed in undergraduate electromagnetics courses at three universities.

**Conceptual approach: The problem of scalabilities and conceptual understanding**

A major challenge for the students as well as the instructors of electromagnetism is creating a conceptual framework of basic definitions, equations, and historical perspectives that constitutes the area of electromagnetism. With over 200 years of systematic experimentation, documentation, and investigation; electromagnetism remains a challenging subject for students of all physical sciences and in particular for electrical engineering.

For the introductory classes in electrical engineering, many programs have transformed the undergraduate as well as graduate level electromagnetic classes to procedures for calculating a set of physical properties; students solve problems by seeking numerical values. Consequently, students try to focus on practical and easy to use equations that lead them to faster calculations (for example with their TI-89 calculators) during examination periods. To practice the process they use the same procedures and equations in their homework and examples. While there is no problem with this approach, generally speaking most students do not achieve a solid conceptual understanding of the subject and spend most of their study time trying to get the "right answers" for the problems.

A good example is the typical transmission line problem, which also manifests itself in the wave propagation formulation. A solid understanding of this issue is an essential part of RF and microwave engineering. Students therefore need to have an in-depth understanding of the basic issues of transmission lines in their introductory classes. Focusing on the typical transmission line problem, the information of a system is given and students must calculate the impedance at the input, find the total voltage at the input, move the appropriate entities to the load end and then find the voltage and current at the load. This process is an effective practice for the student to learn to use the basic concepts of transmission line (positive and negative traveling waves, impedances, etc). However, a majority of the students end up finding the equations to help them shortcut through the process, which will impede their understanding of the essence of the transmission and distributed element behavior of systems that also appear in wave propagation.

Utilization of programs such as MATLAB and MATHCAD will help students spend less time on their calculations with calculators trying to get the right answer. They can set up an M-File in MATLAB and move the appropriate parameters along the transmission line with the right conceptual approach. They can also program different ways to calculate the same parameters and check their answers. Utilizing M-Files will help them scale their problems and use the same basics, by modifying the M-file, for other problems. In addition, with MATLAB tools they can graph different entities on the line and visualize the behaviors in time and/or space which provide a great visual reinforcement of the concepts in applications. This can be enhanced by instructors sharing some of their M-files with the students to lead them in the right direction.

When choosing the above approach, the students will be able to solve problems, understand the concepts, examine their solutions from different perspectives and have a better feeling of the physical meaning of the answers.

Finally, in advanced applications the availability of tool boxes, such as the RF tool box for MATLAB, can accelerate the students' learning and visualization to reinforce the conceptual understanding of the subject.

**MATLAB examples**

MATLAB can be a powerful tool for use in electromagnetics courses and its use has been incorporated in several textbooks such as Wentworth[1]. It can be used as a demonstration tool to clarify important concepts, and can serve as the students' home laboratory, helping to develop their practical understanding of electromagnetics. It is important to note that MATLAB is used in variety of engineering classes and students have good familiarity with this important software package especially when they are at the junior level and also use it in their signals & systems courses. In most schools MATLAB is widely available in engineering laboratories with access available to all faculty and students, mainly for classroom use. Many electrical/computer engineering leading industries use MATLAB and its toolboxes.

***Waves on Transmission Lines***

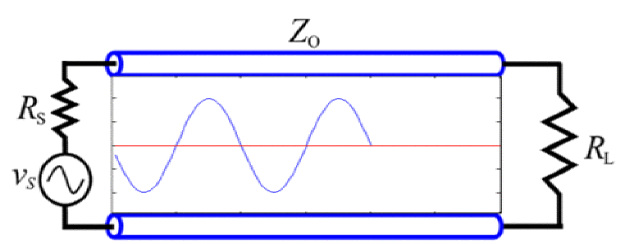
In a transmission lines first approach towards teaching electromagnetics, students are first

Example:

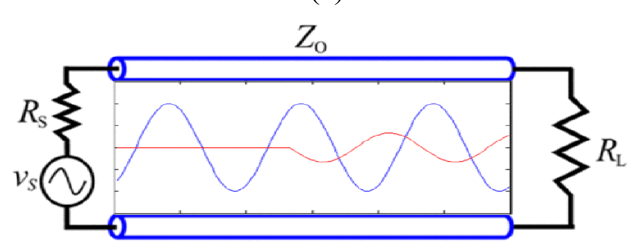
$Z_o = 50\Omega$

$R_L = 100\Omega$

$$\Gamma = \frac{100-50}{100+50} = \frac{1}{3}$$




(a)




(b)

Figure 1: MATLAB movie snapshots taken (a) just before and (b) just after wave is incident on the load. The incident wave is blue and reflected wave is red.

exposed to wave behavior on transmission lines. The concepts of incident and reflected waves can be demonstrated using a MATLAB movie. Figure 1 shows still shots from the movie just before and just after the wave is incident on a mismatched load. In this demonstration, a PowerPoint presentation is used to introduce students to transmission lines. Then, a MATLAB movie (a .WVE file) is inserted in a PowerPoint slide within the T-Line, as shown in the figure. In addition to demonstrating wave behavior on T-Lines, this is an early demonstration of MATLAB in action that will hopefully spark student interest.

Several lectures after students have been introduced to transmission lines, we discuss how a mismatched termination can result in a standing wave pattern on the line, which is simply the superposition of the incident and reflected waves. The concept of voltage standing wave ratio

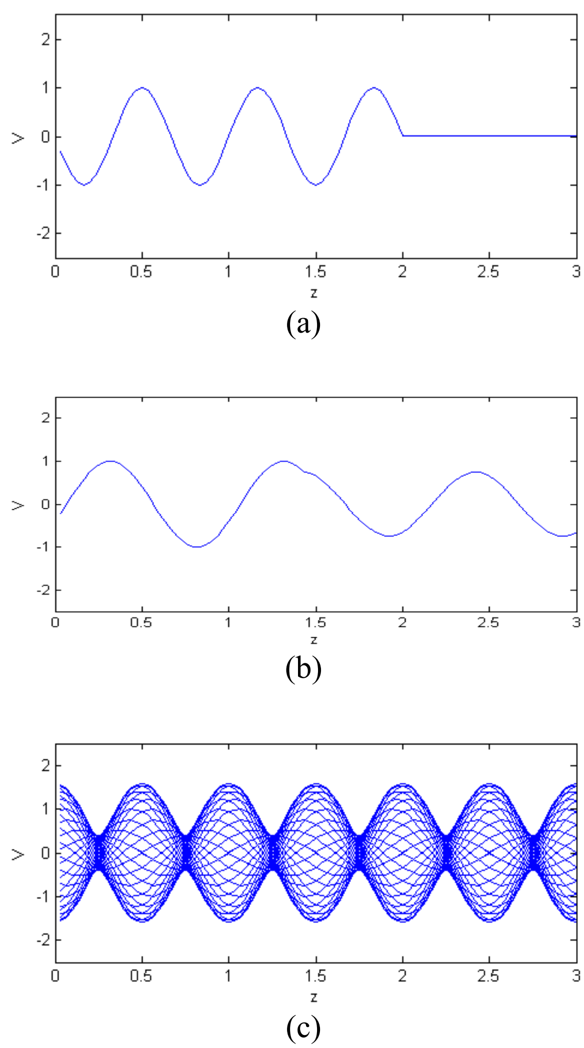



Figure 2: Still shots from the VSWR movie. (a) incident wave, (b) incident and reflected wave, (c) establishment of the standing wave pattern.

(VSWR) is much easier to demonstrate via MATLAB than to explain with equations. Figure 2 shows some still shots at three different points in the movie. First, an incident wave is launched on the line (Figure 2(a)). A portion of this wave reflects (Figure 2(b)). When the reflected portion reaches the input end of the T-line, MATLAB's "hold on" feature is implemented, resulting in the standing wave pattern of Figure 2(c). Students immediately see and understand the concept of standing wave ratio, which can be somewhat challenging to understand without this demonstration.

***Dipole Antenna Analysis***

MATLAB can also be used for numerical analysis of problems that are difficult or impossible to solve analytically. For example, analyzing arbitrary length dipole antennas requires numerical integration to find the pattern solid angle. Students can use MATLAB to transform the integral

$$\Omega_p = \frac{2\pi}{F(\theta)_{\max}} \int \frac{\left[\cos\left(\frac{\beta L}{2}\cos\theta\right) - \cos\left(\frac{\beta L}{2}\right)\right]^2}{\sin\theta} d\theta$$

into a summation equation

$$\Omega_p = \frac{2\pi}{F(\theta)_{\max}} * \sum_{i=1}^{N} \frac{\left[\cos\left(\frac{\beta L}{2}\cos\theta_i\right) - \cos\left(\frac{\beta L}{2}\right)\right]^2}{\sin\theta_i} \Delta\theta$$

for which a MATLAB program can be easily written.

The pattern function of a dipole antenna (termed the beam pattern when it is normalized to its maximum value) can be displayed using MATLAB for an arbitrary length dipole antenna. Students therefore have an antenna design tool. This can be further developed into a movie to demonstrate how the dipole antenna pattern function varies with change in either its length or the operating frequency. Figure 3 shows several still shots of the movie.

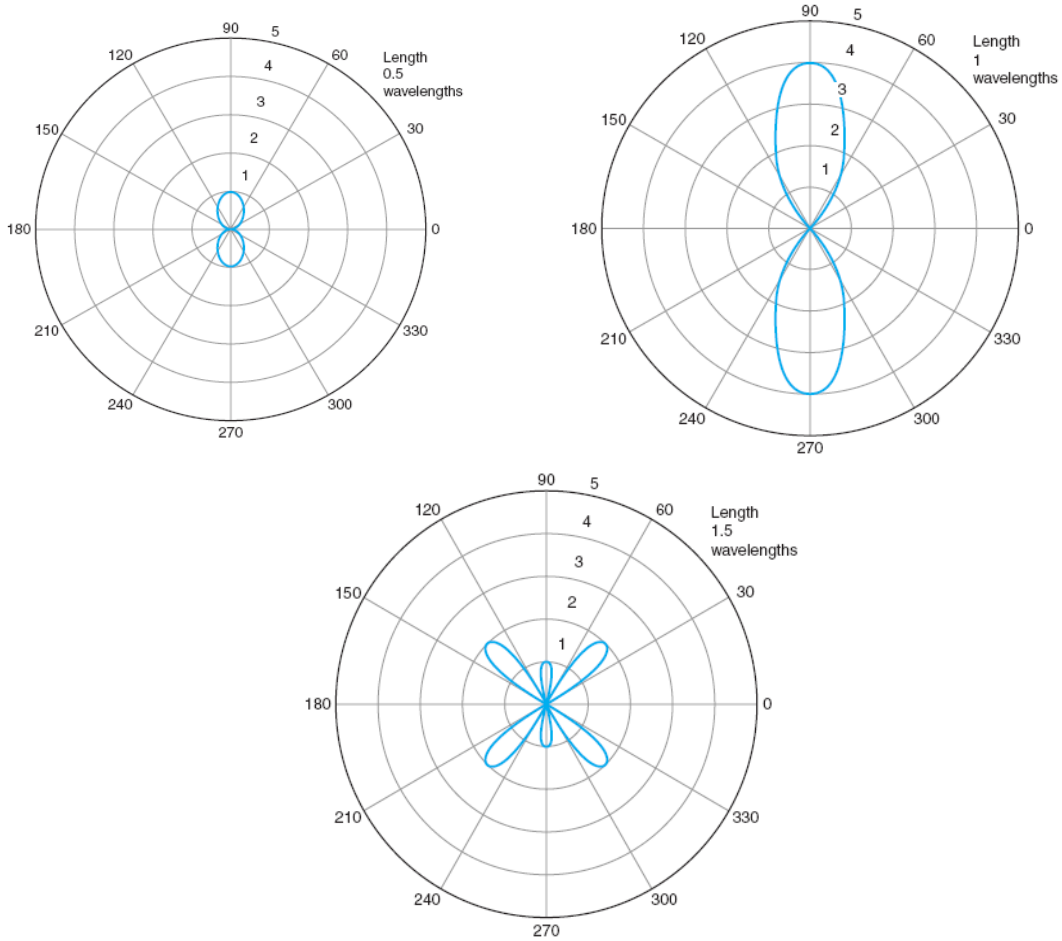



Figure 3: snapshots of dipole antenna pattern function from dipole antenna movie at three dipole lengths.

**MATHCAD examples**

Another important tool is MATHCAD with its symbolic algebra system being useful for engineering courses including electromagnetics, digital signal processing and power systems analysis/design. It is interesting to note that many schools have been using MATHCAD in addition to MATLAB; also the popular Schaum's Outlines[2] is using MATHCAD in solving EM and other engineering problems. Here we present a few examples used in the class. Note that notation, formulas used are those as defined in reference 1.

One example from bioelectromagnetics (important application of the concepts learned in the course) is the propagation parameters computation (propagation constant and impedance) in a given material. Students understand that the parameters are a function of frequency but computation is tedious if tried by hand or by a calculator. It is interesting to show students that complicated expressions (such as input impedance of a lossy transmission line with complex impedances) can be analyzed using MATHCAD. We then show an example of a lossless transmission line terminated in a complex load. Students usually become frustrated when computing, for example, input impedance ($Z_{in}$) and other required variables (e.g., complex power absorbed by the load, $S_L$.) The Smith Chart graphical tool is useful in this part of the course but the results obtained graphically are not precise.

A final example is presented for the VSWR (voltage standing wave ratio) on a transmission line terminated in an impedance resulting in reflection coefficient $\Gamma_L$. Another useful application of MATHCAD is when dispersion is discussed in a transmission line propagating pulses rather than sinusoidal voltages and currents. In this part of the course students are just being introduced to the concepts of Fourier analyses in their signals and systems course. MATHCAD can be very useful in showing different waveforms one obtains in the Fourier Series analysis and graphical representation of periodic rectangular pulse signals.

## MATHCAD EXAMPLE: Muscle Tissue (biological materials) at high frequencies.

Here we compute complex propagation constant in a biological material which has a conductivity of 1.6 S/m (muscle) and relative dielectric constant of 51 at the frequency of 915 MHz. Intrinsic impedance is also calculated.

$f := 915\cdot 10^{6}$ $\qquad \sigma := 1.6$ $\qquad \varepsilon r := 51$

$\varepsilon 0 := 8.854\cdot 10^{-12}$ $\qquad \varepsilon := \varepsilon r\cdot \varepsilon 0$

$\omega := 2\cdot\pi\cdot f$ $\qquad \mu 0 := 4\cdot\pi\cdot 10^{-7}$

$$\alpha := \omega\cdot\sqrt{\left(\mu 0\cdot\frac{\varepsilon}{2}\right)\cdot\sqrt{1+\frac{\sigma^2}{\left(\omega^2\cdot\varepsilon^2\right)}}-\mu 0\cdot\frac{\varepsilon}{2}}$$

$\alpha = 40.472$

$$\beta := \omega\cdot\sqrt{\left(\mu 0\cdot\frac{\varepsilon}{2}\right)\cdot\sqrt{1+\frac{\sigma^2}{\left(\omega^2\cdot\varepsilon^2\right)}}+\mu 0\cdot\frac{\varepsilon}{2}}$$

$\beta = 142.805$ $\qquad j := \sqrt{-1}$

$$\eta := \sqrt{\omega\cdot\frac{\mu 0\cdot j}{(\sigma+\omega\cdot\varepsilon\cdot j)}}$$

$\eta = 46.829 + 13.272i$

## MATHCAD Transmission Line Example with losses

A 100 V source with internal resistance of 40 Ω is connected to a transmission line with characteristic impedance of 60 + j40 Ω, length z = 2m, and propagation constant γ = 1 + j1  1/m. For a load impedance (termination) of 20 + j50 Ω, find the powers absorbed by the load.

$Vs := 100 \qquad Zs := 40 \qquad z := 2 \qquad \gamma := 1 + j \qquad Z0 := 60 + 40j$

$ZL := 20 + 50j$

$$Zin := Z0 \cdot \frac{(ZL + Z0 \cdot \tanh(\gamma \cdot z))}{(Z0 + ZL \cdot \tanh(\gamma \cdot z))} \qquad Zin = 60.184 + 39.117i$$

$$Is := \frac{Vs}{(40 + Zin)} \qquad Is = 0.866 - 0.338i$$

$$\Gamma L := \frac{(ZL - Z0)}{(ZL + Z0)} \qquad \Gamma L = -0.159 + 0.303i$$

$$s := \frac{(1 + |\Gamma L|)}{(1 - |\Gamma L|)} \qquad s = 2.041$$

$$Vin := Zin \cdot Is \qquad Vin = 65.355 + 13.527i$$

$$V0p := \frac{Vin}{(\exp(\gamma \cdot z) + \Gamma L \cdot \exp(-\gamma \cdot z))} \qquad V0p = -1.969 - 8.836i$$

$$VL := V0p \cdot (1 + \Gamma L) \qquad VL = 1.025 - 8.032i$$

$$IL := \frac{VL}{ZL} \qquad IL = -0.131 - 0.073i$$

$$SL := 0.5 \cdot VL \cdot \overline{IL} \qquad SL = 0.226 + 0.565i$$

## MATHCAD EXAMPLE: Lossless Transmission Line

A 60 volts, 100 MHz source with source impedance of 300 Ω is connected to a lossless transmission line of length z = 2m, characteristic impedance of 300 Ω and propagation velocity of $2.5\text{x}10^8$ m/s. We want to compute complex power absorbed by the load impedance of 120 - j60 Ω.

$Vss := 60 \qquad Zs := 300 \qquad f := 1.\cdot 10^8 \qquad up := 2.5\cdot 10^8$

$Z0 := 300 \qquad z := 2 \qquad \beta := 2\cdot\pi\cdot\frac{f}{up}$

$ZL := 120 - 60j \qquad j := \sqrt{-1}$

$\Gamma L := \frac{(ZL - Z0)}{(ZL + Z0)} \qquad \Gamma L = -0.4 - 0.2i$

$$Zin := Z0\cdot\frac{(ZL + Z0\cdot\tan(\beta\cdot z)j)}{(Z0 + ZL\cdot\tan(\beta\cdot z)j)}$$

$Zin = 755.496 - 138.465i$

$Vin := Vss\cdot\frac{Zin}{(Zin + Zs)} \qquad Vin = 43.235 - 2.199i$

$$V0p := \frac{Vin}{(\exp(j\cdot\beta\cdot z) + \Gamma L\cdot\exp(-j\cdot\beta\cdot z))}$$

$V0p = 9.271 + 28.532i$

$VL := V0p\cdot(1 + \Gamma L)$

$VL = 11.269 + 15.265i$

$IL := \frac{VL}{ZL} \qquad IL = 0.024 + 0.139i$

$SL := 0.5\cdot VL\cdot\overline{IL} \qquad SL = 1.2 - 0.6i$

**MATHCAD VSWR Example**

θ = ωt

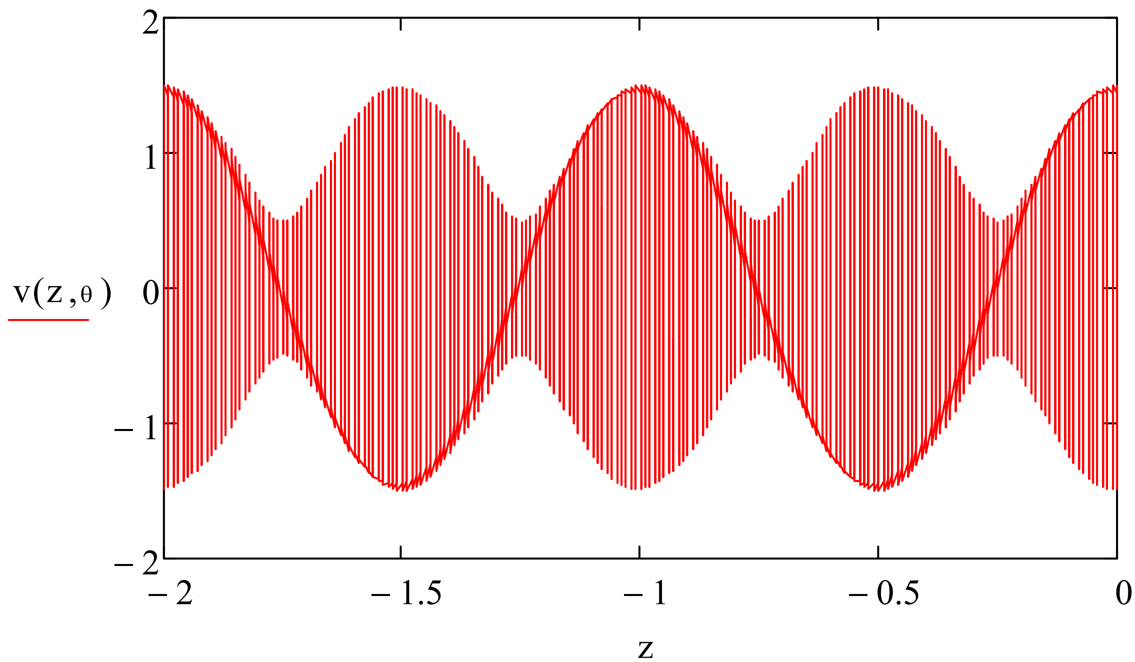
λ = 1 m ; β = 2π

Γ L = 0.5

Vo+ = 1 V ; s = 1.5/0.5 = 3

$z := 0, -.01 .. -2$ $\qquad\qquad$ $\theta := 0, 0.5 .. 2\cdot\pi$

$$v(z,\theta) := \cos(\theta - 2\cdot\pi\cdot z) + 0.5\cdot\cos(\theta + 2\cdot\pi\cdot z)$$



## Conclusions

The subject of electromagnetics (EM) is fundamental in the study of electromechanical energy conversion, communication systems, microwave engineering and radiation/propagation of EM energy. There are important engineering applications that cannot be understood without knowledge of this important subject area within electrical/computer engineering (and physics.) However, many students are apprehensive when taking electromagnetics courses because of the mathematical complexity of the concept involved. Experience by the authors of this paper has shown that software packages such as MATLAB & MATHCAD, if used at the right time/place with proper class examples, can help students better visualize the abstract concepts which are usually part of the EM courses. Other related publications are listed as references [3,4,5].

Code described in this paper and other examples presented at the conference are available at: mosfet.isu.edu/classes/mousavinezhad/ASEE_2010

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