

# MATLAB<sup>®</sup>-Based Electromagnetics

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*To Olivera, Jelena, and Milica*



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# PREFACE

Electromagnetic theory is a fundamental underpinning of technical education, but, at the same time, one of the most difficult subjects for students to master. In order to help address this difficulty and contribute to overcoming it, here is a textbook on electromagnetic fields and waves completely based on MATLAB<sup>®</sup>, and so entitled, simply, *MATLAB<sup>®</sup>-Based Electromagnetics*. This text provides engineering and physics students and other users with an operational knowledge and firm grasp of electromagnetic fundamentals aimed toward practical engineering applications, by teaching them “hands on” electromagnetics through a unique and comprehensive collection of MATLAB computer exercises and projects. Essentially, the book unifies two themes: it presents and explains electromagnetics using MATLAB on one side, and develops and discusses MATLAB for electromagnetics on the other.

The book is designed primarily (but by no means exclusively) for junior-level undergraduate students in electrical and computer engineering, physics, and similar departments, for either two-semester course sequences or one-semester courses, and/or equivalent quarter arrangements. However, it can also be used earlier and later in the curriculum. It covers all important theoretical concepts, methodological procedures, and solution tools in electromagnetic fields and waves for undergraduates – organized in 12 chapters on electrostatic fields; steady electric currents; magnetostatic fields; time-varying electromagnetic fields; uniform plane electromagnetic waves; transmission lines; waveguides and cavity resonators; and antennas and wireless communication systems. It largely follows the organization of *Electromagnetics* by Branislav M. Notaroš, published in 2010 by *Pearson Education*.

On the other hand, the book allows for flexibility in coverage of the material, including the transmission-lines-early and transmission-lines-first approaches. Namely, Chapter 10 (Circuit Analysis of Transmission Lines) discusses only pure circuit-theory concepts, so that it can be taken at any time, along with Sections 6.7 and 6.8, which introduce phasors and complex representatives of time-harmonic voltages and currents.

*MATLAB<sup>®</sup>-Based Electromagnetics* is a self-contained textbook that can be used either as a supplement to any available electromagnetics text (e.g., [1]–[17] in the Bibliography) or as an independent resource. In other words, it is designed either to complement another (currently used or to be adopted) textbook and a variety of teaching styles, as a comprehensive companion adding a very significant MATLAB component to the course, or to serve as a principal resource for a MATLAB-based electromagnetic fields and waves course. In either way, MATLAB exercises are designed to strongly enforce and enhance both theoretical concepts and problem-solving techniques in electromagnetics.

In addition, respective parts of almost all chapters of the book can be effectively incorporated in higher-level courses on antennas, microwave theory and engineering, wave propagation and guidance, advanced electromagnetic theory, computational electromagnetics, electrical machines,

signal integrity, etc. (for instance, see [18]–[34]). Furthermore, the book may be used by students outside of any particular course arrangements and by practicing engineers and scientists as well – to review and solidify the knowledge of fundamentals of electromagnetic fields and waves or certain aspects of electromagnetic theory and applications, now in a MATLAB context. Some may use it, on the other hand, to build and enhance the understanding and command of MATLAB syntax, functionality, and programming, in the framework of electromagnetics. Finally, because of its project-based philosophy and format, the book may be useful for distance learning, online courses, and other forms of nontraditional course delivery.

### Overall distinguishing features of MATLAB<sup>®</sup>-Based Electromagnetics:

- The book provides two interwoven themes: presentation and study of *electromagnetics using MATLAB* and development and discussion of *MATLAB for electromagnetics*
- Can be used to either *complement* available electromagnetics text, or as an *independent* resource
- Contains *389 MATLAB computer exercises and projects*, covering and reinforcing practically all important theoretical concepts, methodologies, and problem-solving techniques in electromagnetic fields and waves (see Appendix 3 for a full *List of MATLAB Exercises*)
- Designed primarily *for undergraduate electromagnetics*, but can also be used *in follow-up courses* on antennas, propagation, microwaves, advanced electromagnetic theory, computational electromagnetics, electrical machines, signal integrity, etc.
- Provides a *theoretical overview* at the start of *each section* within each chapter of the book
- Maintains a favorable balance of MATLAB exercises between *static (one third) and dynamic (two thirds) topics*
- Offers *MATLAB exercises at all levels of difficulty*, from a few lines of MATLAB code, to those requiring a great deal of initiative and exploration
- Contains *125 TUTORIALS with detailed solutions* merged with *listings of MATLAB codes (m files)*; a demo tutorial for every class of MATLAB problems and projects is provided
- Gives *98 HINTS with guidance on the solution*, equations, and programming, often with portions of the code and/or resulting graphs and movie snapshots for validation
- Features *48 3-D and 2-D movies developed and played in MATLAB*, which are extremely valuable for interactive visualizations of fields and waves
- Displays *133 figures generated in MATLAB* with plots of geometries of structures, vector fields, guided and unbounded waves, wave polarization curves, Smith charts, transient signals, antenna patterns, etc.
- Presents *16 graphical user interfaces (GUIs) built in MATLAB* to calculate and display parameters and characteristics of various electromagnetic structures, materials, and systems, selected from a pop-up menu

- Offers *130 MATLAB exercises recommended to be done also “by hand”* – i.e., not using MATLAB, thus serving as traditional written problems

MATLAB<sup>®</sup> (by *MathWorks, Inc.*) is chosen not only for its very high quality and versatility, but because it represents a generally accepted standard in science and engineering education worldwide (e.g., [35]–[44]). Assignments of computer exercises along with traditional “by hand” problems help students develop a stronger intuition and a deeper understanding of electromagnetics. Moreover, this approach actively challenges and involves the student, providing additional benefit as compared to a passive computer demonstration. This book provides abundant opportunities for instructors to assign in-class and homework projects, and for students to engage in independent learning. MATLAB exercises are also ideal for interactive in-class explorations and discussions (*active teaching and learning*), and for team work and peer instruction (*collaborative teaching/learning*).

On the other side, studying and practicing these diverse exercises allows students to gain comprehensive and operational knowledge and skills in concepts and techniques of MATLAB use and programming. These skills can then be used effectively and implemented in other areas of study, including other courses in the curriculum.

To make this text self-contained and easy to use, each section within each chapter begins with a brief theoretical overview, which is followed by MATLAB exercises strongly coupled to the theory. Some theoretical details, along with abundant applications, are introduced through exercises themselves.

Each book section contains a large number of tutorial exercises with detailed solutions merged with listings of MATLAB codes (m files). TUTORIALS explain every step, with ample discussions of approaches, programming strategies, MATLAB formalities, and alternatives. They are written so that even a reader with no prior experience with MATLAB can fully understand them. Most importantly, all new concepts, approaches, and techniques in MATLAB programming as applied to electromagnetic fields and waves are covered with TUTORIALS. With a total of 125 TUTORIALS, for each class and type of MATLAB problems and projects there is always a demo exercise or set of exercises with complete detailed tutorials and code listings to provide students with guidance for completing similar exercises on their own. This is especially notable for exercises of intermediate and advanced levels of difficulty.

In addition to exercises with TUTORIALS, there are 98 exercises with HINTS, which provide guidance on the solution, equations, and programming, sometimes with most critical portions of MATLAB codes for the problem. In many cases, they present the resulting graphs and movie snapshots, so that readers can see what exactly they are expected to do and can verify and validate their codes. The exercises include 48 movies developed and played in MATLAB, 133 figures generated in MATLAB, and 16 GUIs built in MATLAB.

However, even the exercises with TUTORIALS can be assigned for homework or classwork, as their completion requires putting together a MATLAB code from the provided portions of the code listing (note that in some tutorials, some standard parts of the code, like data input, are omitted); actual running of the code; and generation and presentation of results. It is recommended that these exercises be a part of every homework assignment.

MATLAB exercises require a great deal of analytical preparation, manipulation with equations, and conceptual, strategic, and calculative analysis of problem situations. Thus, they are a great complement or often an adequate substitute for traditional written problems. Moreover, 130 exercises are designated as two-purpose problems: as computer-based MATLAB problems and as conventional “by hand” computational problems (these exercises are marked by H in the book). Of course, the reader can compare and cross-validate the results from MATLAB and those obtained “by hand.” In addition, these problems (and their variations) can be given as traditional problems for homework and on exams. Note, however, that many other (unmarked) exercises can entirely, or in large part, be solved without MATLAB. In general, solving the problems and studying the topics both analytically and using MATLAB is most beneficial.

MATLAB codes described (and listed) in TUTORIALS or proposed in other exercises provide prolonged benefits of learning. By running codes; generating results, figures, and diagrams; playing movies and animations; and solving a large variety of problems in MATLAB, in class, with peers in study groups, or individually, students gain a deep understanding of electromagnetics. Most importantly, this book capitalizes on a win-win combination of pedagogical benefits of MATLAB-based electromagnetics education and students’ computer-related skills and interests. As opposed to other available electromagnetics texts that feature some use of MATLAB, this text is by far the most complete and ambitious attempt to use MATLAB across all elements of electromagnetics education.

**Some specific technical and pedagogical features of the content of MATLAB<sup>®</sup>-Based Electromagnetics and its MATLAB exercises, projects, codes, and solutions:**

- *Field computation and visualization in MATLAB:*
  - ◇ MATLAB codes for computing and plotting electric and magnetic forces and fields (vectors) due to arbitrary 3-D arrays of stationary and moving charges; movie of electron travel in a magnetic field
  - ◇ Calculation and visualization of boundary conditions for oblique and horizontal boundary planes between arbitrary media, without and with surface charges/currents on the plane
  - ◇ Calculations and movies of electromagnetic induction due to moving and rotating loops in various magnetic fields
  - ◇ Graphical representation of complex numbers and movies of voltage and current phasor rotation in the complex plane
  - ◇ Symbolic computation of  $E$  and  $H$  fields and transmitted power for arbitrary TE and TM modes in a rectangular metallic waveguide, and of fields and stored energy in a rectangular cavity resonator
- *Computation and visualization of uniform plane waves in MATLAB:*
  - ◇ 2-D and 3-D movies visualizing attenuated and unattenuated traveling and standing uniform plane electromagnetic waves in different media

- ◇ 2-D and 3-D movies and plots of circularly polarized (CP) and elliptically polarized (EP) waves; analysis and movie visualization of changes of wave polarization and handedness due to travel through anisotropic crystals
- ◇ 3-D and 2-D movies of incident, reflected, and transmitted (refracted) plane waves for both normal and oblique incidences on both perfectly-conducting and dielectric boundaries, transient processes and steady states
- ◇ Computation and visualization in MATLAB of angular dispersion of a beam of white light into its constituent colors in the visible spectrum using a glass prism
- *Symbolic and numerical programming in MATLAB:*
  - ◇ Symbolic differentiation and integration in all coordinates, symbolic Maxwell's equations, volumetric power/energy computations, conversion from complex to time domain, radiation integrals, etc.
  - ◇ Numerical differentiation and integration, various types of finite differences and integration rules, vector integrals, Maxwell's equations, optimizations, numerical solutions to nonlinear equations, etc.
- *Field and circuit analysis of transmission lines in MATLAB:*
  - ◇ GUI for primary and secondary circuit parameters of multiple transmission lines
  - ◇ MATLAB analysis and design (synthesis) of microstrip and strip lines with fringing
  - ◇ Numerical solutions and complete designs in MATLAB of impedance-matching transmission-line circuits with shunt and series short- and open-circuited stubs, including finding the stub location
- *Transmission-line analysis and design using the Smith chart in MATLAB:*
  - ◇ Construction of the Smith chart in MATLAB, adding dots of data on the chart, movies of Smith chart calculations on transmission lines, movies finding load impedances using the Smith chart
  - ◇ Searching for a desired impedance along a line in a numerical fashion and complete design in a Smith chart movie of impedance-matching transmission-line circuits with series stubs
- *MATLAB calculation of transients on transmission lines with arbitrary terminations:*
  - ◇ General MATLAB code for calculation of transients on transmission lines; plotting transient snapshots and waveforms; transient responses for arbitrary step/pulse excitations and matching conditions
  - ◇ Numerical simulation in MATLAB of a bounce diagram: bounce-diagram matrix; extracting signal waveforms/snapshots from the diagram; complete MATLAB transient analysis using bounce diagrams
  - ◇ Complete transient analysis in MATLAB of transmission lines with reactive loads and pulse excitation, with the use of an ordinary differential equation (ODE) solver; generator voltage computation

- *MATLAB analysis and visualization of antennas, wireless systems, and antenna arrays:*
  - ◇ Computation of the near field, radiation integral, far field, radiation and ohmic resistances, radiation efficiency, directivity, and gain of wire antennas
  - ◇ Functions in MATLAB for generating 3-D polar pattern plots of arbitrary radiation functions and for cutting a 3-D pattern in three characteristic planes to obtain and plot 2-D polar radiation patterns
  - ◇ Playing a movie to visualize the dependence of the radiation pattern on the electrical length of wire antennas
  - ◇ 3-D visualization of a wireless system with arbitrarily positioned and oriented wire dipole antennas; complete MATLAB analysis of systems with nonaligned antennas, including CP and EP transmitting antennas
  - ◇ Computation of the array factor of arbitrary linear arrays of point sources, generation of 3-D radiation pattern plots and 2-D pattern cuts in characteristic planes; complete MATLAB analysis of linear arrays
  - ◇ Implementation and visualization of the pattern multiplication theorem for antenna arrays in  $xy$ -,  $xz$ -, and  $yz$ -planes; complete MATLAB analysis of uniform and nonuniform arrays of arbitrary antennas (not just point sources)
- *MATLAB solutions to nonlinear problems:*
  - ◇ Graphical and numerical solutions for a simple nonlinear electric circuit
  - ◇ Complete numerical solutions in MATLAB for simple and more complex nonlinear magnetic circuits, movies of magnetization–demagnetization processes
- *Computational electromagnetic techniques in MATLAB:*
  - ◇ MATLAB codes based on the method of moments (MoM) for 3-D numerical analysis of charged metallic bodies (plates, boxes, and a parallel-plate capacitor); preprocessing and postprocessing
  - ◇ MATLAB codes for 2-D finite-difference (FD) numerical solution of Laplace’s equation, based on both iterative and direct solutions of FD equations; potential, field, and charge computations

*Pearson eText* of the book, with full-color figures, is available on the Companion Website (CW):

[www.pearsonhighered.com/notaros](http://www.pearsonhighered.com/notaros)

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Please send comments, suggestions, questions, and/or corrections to [notaros@colostate.edu](mailto:notaros@colostate.edu).

*All listed MATLAB codes and parts of codes may be used only for educational purposes associated with the book, MATLAB<sup>®</sup>-Based Electromagnetics.*

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Fort Collins, Colorado*

## m Files on Instructor Resources

On Instructor Resources (IR), the book provides MATLAB codes (m files) for *all* MATLAB exercises, separated into 12 folders (chapter folders). Code listings in TUTORIALS, where they appear merged with the narratives of the solutions to exercises, are obtained directly from the corresponding m files provided on IR. All figures appearing in MATLAB exercises, including the snapshots of MATLAB movies, GUIs, etc., as well as all other numerical and textual results given in the exercises, are generated using the m files from these folders.

There are about 560 m files – for 389 MATLAB exercises; some exercises have multiple m files, as their solutions consist of more than one function or the main program and a function, etc. Files with functions (written in MATLAB) have descriptive names, e.g., *bounceDiagram.m*. Files with main MATLAB programs are named according to the numeration/labeling of exercises: for instance, main program for *MATLAB Exercise 12.32* is in file *ME12\_32.m*. So, the “recipe” for finding the m file for a given MATLAB exercise is simple: (1) if the exercise features a main MATLAB program, find the m file with the name matching the exercise label (number) in the respective chapter folder; (2) in the case of a function exercise, look for the function name in the statement of the exercise, and find the m file with that name. For convenience, however, the names of respective m files are explicitly specified in all MATLAB exercises in the book. *List of MATLAB Exercises* in Appendix 3 contains the full list of m files as well.

Files for GUIs built in MATLAB are stored in separate folders (subfolders) named after the corresponding MATLAB exercises, within the respective chapter folders. For example, files for the GUI from *MATLAB Exercise 2.13* are in subfolder *ME2\_13(GUI)* in *Chapter\_2* folder. A GUI folder always includes the GUI control function file (e.g., *capCalc1.m*) and the GUI layout file with the same name and fig extension (*capCalc1.fig*). It may also include one or more other functions (m files), for specific calculations or other tasks. Some GUI folders contain a number of png files (e.g., *coaxcable.png*), with pictures (drawings) of structures (previously created by another computer program for drawing), which are imported in the GUI control function.

The provided codes are run in MATLAB in a standard fashion: by selecting, opening, and running the appropriate m file in the appropriate chapter (or GUI) folder.

The material on IR, including all 12 chapter folders with m files, is meant *for instructors only*. In addition to serving as a complement to the *Instructor’s Solutions Manual* for the book, which is also available on IR, it provides an invaluable resource for lectures, recitations, and class demonstrations. Namely, any and all MATLAB codes for the current class topic, including codes for movies; calculators; GUIs; numerical solvers; data processors and tabulators; diagram and figure plotters; conceptual demonstrators; etc., can readily be run and discussed, in support of a theoretical presentation, or as a problem session.

*Any of the provided m files on Instructor Resources and any of the included MATLAB codes or any part of a code may be used only for educational purposes associated with the book, MATLAB®-Based Electromagnetics.*