ELECTROMAGNETICS

COMPANION WEBSITE

MATLAB® Exercises (for Chapters 1-14)

Branislav M. Notaroš

Department of Electrical and Computer Engineering
Colorado State University

www.pearsonhighered.com/notaros

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Preface to MATLAB® Exercises

MATLAB® Exercises in Electromagnetics, an e-supplement to *Electromagnetics* by Branislav M. Notaroš (from now on, referred to as "the book"), provides an extremely large and comprehensive collection of MATLAB computer exercises and projects, strongly coupled to the book material, both the theory and the worked examples, as well as the end-of-chapter problems. MATLAB® (by MathWorks, Inc.) is chosen not only for its very high quality and versatility, but principally because it is nowadays a generally accepted standard in science and engineering education worldwide. There are a total of 478 MATLAB exercises, which are referred to regularly within all book chapters, at the ends of sections, to supplement problems and conceptual questions. Assignments of computer exercises in parallel with traditional problems can help students develop a stronger intuition and a deeper understanding of electromagnetics and find it more attractive and likable. Moreover, this approach, requiring MATLAB programming, actively challenges and involves the student, providing additional benefit as compared to a passive computer demonstration. This resource provides abundant opportunities for instructors for assigning in-class and homework projects – if so desired.

MATLAB Exercises cover all important theoretical concepts, methodological procedures, and solution tools in electromagnetic fields and waves for undergraduates – in electrostatic fields, steady electric currents, magnetostatic fields, slowly time-varying (low-frequency) electromagnetic fields, rapidly time-varying (high-frequency) electromagnetic fields, uniform plane electromagnetic waves, transmission lines, waveguides and cavity resonators, and antennas and wireless communication systems. They are organized in 14 chapters following the organization of the book. The exercises are subdivided also in sections, to make the correspondence with the book material even more apparent and easy to track. All exercises are pedagogically exceptionally instructive and very tightly interwoven with the theory and examples in the book. They are designed to strongly reinforce and enhance both the theoretical concepts and problem-solving techniques and skills in electromagnetics.

On the other side, by studying and practicing through these numerous and very diverse exercises, students and other readers will gain a really comprehensive and truly operational knowledge and skills in concepts and techniques of MATLAB programming – overall, apart from immediate applications to electromagnetics. These skills can then readily and effectively be used and implemented in many other areas of study and endeavor, including other courses in the curriculum.

Each part of this collection contains a large number of tutorial exercises with detailed completely worked out solutions merged with listings of MATLAB codes (m files). Tutorials show and explain every step, with ample discussions of approaches, programming strategies, MATLAB formalities, and alternatives. They are written in a way that can be followed and fully understood, and then effectively applied in similar situations, even by a reader with no prior experience with MATLAB. 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 135 tutorials – for each class and type of MATLAB problems and projects in electromagnetic, there is always a demo exercise or set of exercises with complete detailed tutorials and code listings, providing the students and other readers with all necessary instruction and guidance to be able to do all similar exercises entirely on their own, and to complete all homework assignments and class projects. In addition to exercises with TUTORIALS, there are a large number (100) of exercises with HINTS, which provide guidance on the solution, equations, and programming, sometimes with most critical portions of MATLAB codes for the problem, or with 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.

However, even the exercises with TUTORIALS can be assigned for homework and classwork for students, as their completion requires not only full understanding of the tutorial, but also putting together a MATLAB code from the provided portions of the code listing, intercepted with portions of narrative, and actual running of the code and generation and presentation of results. It is in fact recommended that these exercises, being so numerous and uniformly distributed over the book, be made a part of every homework assignment within a given topic or class of exercises or projects.

◇ **Overall distinguishing features of MATLAB Exercises in Electromagnetics:**

- *478 MATLAB computer exercises and projects* covering and reinforcing all important theoretical concepts, methodologies, and problem-solving techniques in electromagnetics for undergraduates
- *Balance of MATLAB exercises in static and dynamic topics*; balance of fields (static, quasistatic, and rapidly time-varying) and waves (uniform plane waves, transmission lines, waveguides, and antennas)
- *135 TUTORIALS with detailed completely worked out solutions* merged with *listings of MATLAB codes (m files)*; there is a demo tutorial for every class of MATLAB problems and projects
- *100 HINTS providing guidance on the solution*, equations, and programming, often with portions of the code and/or resulting graphs and movie snapshots for validation
- *58 3-D and 2-D movies developed and played in MATLAB*; apart from pedagogical benefits of their development, these animations are extremely valuable for interactive visualizations of fields and waves
- *156 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.
- *16 graphical user interfaces (GUIs) built in MATLAB* to calculate and display parameters and characteristics of various electromagnetic structures, materials, and systems, selected in a pop-up menu

◇ **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.

◇ **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

◇ **MATLAB solutions to nonlinear problems:**

- Graphical and numerical solutions for a simple nonlinear electric circuit
- Complete numerical solutions in MATLAB for simple and complex nonlinear magnetic circuits, movies of magnetization-demagnetization processes, solutions and movies of energy of nonlinear circuits
- Numerical solution for electromagnetic induction in coils with nonlinear ferromagnetic cores for given piece-wise linear hysteresis loops

◇ **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
- Calculations and movies of electromagnetic induction due to rotating loops in various magnetic fields

- Calculation and visualization of all sorts of boundary conditions for oblique, horizontal, and vertical boundary planes between arbitrary media, without and with surface charges/currents on the plane
- 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 and elliptically polarized 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 PEC 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

◇ **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 – multiple solutions

◇ **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:**

- 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 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 analysis of linear arrays
- Implementation and visualization of the pattern multiplication theorem for antenna arrays – in xy-, xz-, and yz-planes; complete analysis of uniform and nonuniform arrays of arbitrary antennas

In this supplement, chapters, sections, examples, problems, equations, and figures from the book (*Electromagnetics*) are referred to in exactly the same way as within the book itself. For instance, Chapter 1, Section 1.1, Example 1.1, Problem 1.1., Eq.(1.1), and Fig.1.1 indicate reference to the first chapter, first section, first example, first problem, first equation, and first figure, respectively, in the book. On the other hand, with MATLAB Exercise 1.1, Eq.(M1.1), and Fig.M1.1, we refer to the first MATLAB exercise, first equation, and first figure in the MATLAB supplement.

I would like to acknowledge and express special thanks and sincere gratitude to my Ph.D. students Ana Manić, Nada Šekeljić, and Sanja Manić for their truly outstanding work and invaluable help in writing this supplement and MATLAB computer exercises, tutorials, and codes.

Branislav M. Notaroš
Fort Collins, Colorado

LIST OF MATLAB EXERCISES IN ELECTROMAGNETICS

ME 1.25 **Cylindrical to Cartesian coordinate conversion.** (function `cyl2Car.m`)

ME 1.26 **Cartesian to spherical coordinate conversion.** (function `car2Sph.m`)

ME 1.27 **Spherical to Cartesian coordinate conversion.** (function `sph2Car.m`)

ME 1.28 **Cylindrical to spherical coordinate conversion.** (function `cyl2Sph.m`)

ME 1.29 **Spherical to cylindrical coordinate conversion.** (function `sph2Cyl.m`)

ME 1.30 **GUI for different coordinate conversions.** (function `cs2cs.m`) HINT

ME 1.31 **Symbolic gradient in Cartesian coordinates.** (function `gradCar.m`) HINT

ME 1.32 **Symbolic gradient in cylindrical coordinates.** (function `gradCyl.m`)

ME 1.33 **Symbolic gradient in spherical coordinates.** (function `gradSph.m`)

ME 1.34 **Field from potential, in three coordinate systems.**

ME 1.35 **Direction of the steepest ascent.**

Section 1.11 3-D and 2-D Electric Dipoles

ME 1.36 **Equipotential lines for a small electric dipole.** HINT

ME 1.37 **Visualizing the electric dipole field.**

ME 1.38 **Equipotential lines for a line dipole.**

ME 1.39 **Symbolic expression for the line dipole field.**

Section 1.13 Applications of Gauss' Law

ME 1.40 **Sphere with a nonuniform volume charge.**

Section 1.15 Divergence

ME 1.41 **Symbolic divergence in Cartesian coordinates.** (function `divCar.m`) TUTORIAL

ME 1.42 **Symbolic divergence in cylindrical coordinates.** (function `divCyl.m`)

ME 1.43 **Symbolic divergence in spherical coordinates.** (function `divSph.m`)

ME 1.44 **Charge from field, in three coordinate systems.**

ME 1.45 **Gauss' law – planar, cylindrical, and spherical symmetries.**

Section 1.20 Method of Moments for Numerical Analysis of Charged Metallic Bodies

ME 1.46 **Main MoM matrix, for arbitrary charged body.** (function `matrixA.m`) TUTORIAL

ME 1.47 **Preprocessing of geometrical data for the MoM matrix.** (function `localCoordinates.m`)

ME 1.48 **Total charge, based on the MoM analysis.** (function `totalCharge.m`)

ME 1.49 **MoM-based MATLAB program for a charged plate.** TUTORIAL

ME 1.50 **MoM program for a rectangular charged plate.**

ME 1.51 **MoM-based MATLAB program for a charged cube.** HINT

ME 1.52 **MoM program for a charged parallelepiped.**

ME 10.9 **Reflection coefficient for normal incidence on a penetrable interface.** (function `gammaReflCoef.m`) TUTORIAL

ME 10.10 **Transmission coefficient for normal incidence.** (function `tau.m`)

ME 10.11 **2-D movie of incident, reflected, and transmitted transient fields.** TUTORIAL

ME 10.12 **Normal incidence on the interface of a lossy medium.** HINT

ME 10.13 **3-D MATLAB movie of normal incidence, reflection, and transmission.** HINT

ME 10.14 **Array factor for waves in the complex plane – movie.** TUTORIAL

ME 10.15 **Standing wave ratio.**

ME 10.16 **Wave impedance.** (function `waveImpedance.m`)

Section 10.3 Surface Resistance of Good Conductors

ME 10.17 **Surface resistance function.** (function `surfResistance.m`)

ME 10.18 **Surface resistance of copper and zinc – versus frequency.** HINT

Section 10.5 Oblique Incidence on a Perfect Conductor

ME 10.19 **3-D movie of oblique incidence, normal polarization, on a PEC plane.** TUTORIAL

ME 10.20 **3-D movie of oblique incidence on a PEC – parallel polarization.**

Section 10.7 Oblique Incidence on a Dielectric Boundary

ME 10.21 **Fresnel's reflection coefficients for normal and parallel polarizations.** (function `gammaFresnel.m`)

ME 10.22 **Fresnel's transmission coefficients.** (function `tauFresnel.m`)

ME 10.23 **3-D movie of oblique incidence, parallel polarization, on a dielectric interface.** TUTORIAL

ME 10.24 **Oblique incidence, normal polarization, on a dielectric interface.**

ME 10.25 **Prism function – for computation of light beams in a glass prism.** (function `prismFunc.m`) TUTORIAL

ME 10.26 **Angular dispersion of white light by a glass prism.** TUTORIAL

ME 10.27 **Variations of the light dispersion experiment with a glass prism.**

Section 10.8 Total Internal Reflection and Brewster Angle

ME 10.28 **Brewster angle.** (function `BrewsterAngle.m`)

ME 10.29 **Plots of Fresnel's reflection coefficients and Brewster angle.** HINT

Section 10.9 Wave Propagation in Multilayer Media

ME 10.30 **Lossless three-media structure.** (function `threeMediaLossless.m`)

ME 10.31 **Lossy three-media structure.** (function `threeMediaLossy.m`)

ME 12.48 **Steady state on a line with a step excitation.** (functions `steadyStateVoltage.m` and `steadyStateCurrent.m`)

ME 12.49 **General code for calculation of transients on a transmission line.** (function `signalTL.m`) TUTORIAL

ME 12.50 **Plotting transient snapshots and waveforms on transmission lines.** (function `TLplot.m`) TUTORIAL

ME 12.51 **Complete transient analysis in MATLAB, both line ends unmatched.** TUTORIAL

ME 12.52 **Complete MATLAB analysis, matched generator, open-circuited line.**

ME 12.53 **Matched generator, short-circuited line.**

ME 12.54 **Complete transient analysis, ideal generator, open-circuited line.** HINT

ME 12.55 **Short-circuited line with an ideal generator.**

ME 12.56 **Current-intensity transients – complete MATLAB analysis.**

Section 12.16 Analysis of Transmission Lines with Pulse Excitations

ME 12.57 **Pulse response of a transmission line – from step analysis.** HINT

ME 12.58 **Direct pulse analysis of a line – implementing a pulse excitation.** HINT

ME 12.59 **Overlapping pulses at the load – pulse response from step analysis.**

ME 12.60 **Overlapping pulses at the load – direct pulse analysis.**

ME 12.61 **Bipolar triangular pulse response – complete MATLAB analysis.** HINT

ME 12.62 **Effects of a finite rise time of step signals – complete MATLAB analysis.** HINT

ME 12.63 **Evaluation of current-intensity responses to pulse excitations.**

Section 12.17 Bounce Diagrams

ME 12.64 **Numerical simulation of a bounce diagram: bounce-diagram matrix.** (function `bounceDiagram.m`) TUTORIAL

ME 12.65 **Extracting a signal waveform from the bounce diagram.** (function `zBD.m`) TUTORIAL

ME 12.66 **Extracting a signal snapshot from the bounce diagram.** (function `timeBD.m`) TUTORIAL

ME 12.67 **Voltage bounce diagram and waveforms – complete MATLAB analysis.** TUTORIAL

ME 12.68 **Current bounce diagram and waveforms – complete MATLAB analysis.**

ME 12.69 **Another MATLAB solution using bounce diagrams: voltage plots.**

ME 12.70 **Another MATLAB solution using bounce diagrams: current plots.**

Section 12.18 Transient Response for Reactive or Nonlinear Terminations

ME 12.71 **Time derivative function for ordinary differential equation solver.** (function `ODE.m`) TUTORIAL

ME 12.72 **Line with an RL load – complete analysis in MATLAB.** TUTORIAL

ME 12.73 **Generator voltage computation for a line with an RL load.** TUTORIAL

ME 13.20 Wave impedance of TE waves in a rectangular waveguide. (function `TEWaveImpedance.m`)

ME 13.21 TM wave impedance. (function `TMWaveImpedance.m`)

ME 13.22 Wave impedance plot for the dominant mode. HINT

ME 13.23 Wave impedance plot for the lowest TM mode.

Section 13.8 Power Flow Along a Waveguide

ME 13.24 Transmitted power along a waveguide, symbolic integration. (function `transmittedPower.m`) TUTORIAL

ME 13.25 Symbolic computation of power, arbitrary TE mode. TUTORIAL

ME 13.26 Symbolic computation of power, arbitrary TM mode.

ME 13.27 Power transfer by TE_{02} and TE_{11} wave modes.

ME 13.28 Power transfer by TM_{21} wave mode.

Section 13.9 Waveguides with Small Losses

ME 13.29 Usable frequency range of a standard waveguide. (function `usableFreqRange.m`)

ME 13.30 Attenuation coefficient for the waveguide conductor, dominant mode. (function `alphaCondTE10.m`)

ME 13.31 Attenuation coefficient for the waveguide dielectric, any mode. (function `alphaDiel.m`)

ME 13.32 Plots of attenuation coefficients in the usable frequency range. HINT

Section 13.10 Waveguide Dispersion and Wave Velocities

ME 13.33 Phase velocity in a rectangular waveguide. (function `waveguidePhaseVelocity.m`)

ME 13.34 Waveguide group velocity. (function `waveguideGroupVelocity.m`)

ME 13.35 Guide wavelength. (function `guideWavelength.m`)

ME 13.36 Phase and group velocities in a K-band waveguide.

ME 13.37 Plots of phase and group velocities vs. frequency, several modes. HINT

ME 13.38 Plots of phase and group velocities vs. frequency, several dielectrics.

Section 13.12 Rectangular Cavity Resonators

ME 13.39 Resonant frequency of an arbitrary cavity mode. (function `resoFreq.m`)

ME 13.40 Field computation for an arbitrary TE mode in a resonant cavity. (functions `ExTECavity.m`, `EyTECavity.m`, `HxTECavity.m`, `HyTECavity.m`, and `HzTECavity.m`) HINT

ME 13.41 Field computation for an arbitrary TM cavity mode. (functions `ExTMCavity.m`, `EyTMCavity.m`, `EzTMCavity.m`, `HxTMCavity.m`, and `HyTMCavity.m`)

ME 13.42 GUI with field plots for the dominant cavity mode. HINT

Section 13.13 Electromagnetic Energy Stored in a Cavity Resonator

ME 13.43 Stored energy, any TE or TM cavity mode, symbolic integration. (function `storedEnergy.m`) HINT

ME 14.19 **3-D and 2-D radiation patterns of a Hertzian dipole.** HINT

ME 14.20 **Radiation patterns of a traveling-wave antenna.**

ME 14.21 **Movie demonstration that Hertzian dipole pattern cuts are circles.** TUTORIAL

Section 14.8 Wire Dipole Antennas

ME 14.22 **Characteristic radiation function of a half-wave dipole.** (function `HalfWaveDipoleF.m`) TUTORIAL

ME 14.23 **Radiation patterns of a half-wave dipole.** HINT

ME 14.24 **Numerical integration by Simpson's rule.** (function `Simpson.m`) TUTORIAL

ME 14.25 **Radiation resistance of a half-wave dipole using Simpson's rule.**

ME 14.26 **Directivity of a half-wave dipole.**

ME 14.27 **Radiation function and pattern plots of an arbitrary wire dipole.** HINT

ME 14.28 **Dependence of radiation pattern on antenna length – movie.** (function `patternVsLengthMovie.m`) TUTORIAL

ME 14.29 **Playing the pattern movie for different dipole lengths.** TUTORIAL

ME 14.30 **Pattern movie for traveling-wave antennas of different lengths.**

Section 14.10 Monopole Antennas

ME 14.31 **Radiation patterns of a quarter-wave monopole.**

ME 14.32 **Multiple reflections from ionosphere – path calculations.** (function `ionosphMultipleReflPath.m`) TUTORIAL

ME 14.33 **Multiple reflections from ionosphere – field calculations.** HINT

Section 14.11 Magnetic Dipole (Small Loop) Antenna

ME 14.34 **Radiation patterns of a small loop antenna.**

Section 14.12 Theory of Receiving Antennas

ME 14.35 **Geometrical preprocessing for arbitrarily oriented T-R antennas.** (function `antennaXYZ.m`) TUTORIAL

ME 14.36 **Visualization of a wireless system with two antennas.** (function `antennaDraw.m`) TUTORIAL

ME 14.37 **Wireless link with nonaligned antennas – complete analysis in MATLAB.** TUTORIAL

ME 14.38 **Switching places of T-R antennas – complete analysis in MATLAB.**

ME 14.39 **Reception of a CP wave by a wire dipole – complete analysis in MATLAB.** HINT

ME 14.40 **Reception of an EP wave – complete analysis in MATLAB.**

Section 14.14 Friis Transmission Formula for a Wireless Link

ME 14.41 **Attenuation in a wireless link, Friis transmission formula.** (function `attenuationFriis.m`) TUTORIAL