

ELECTROMAGNETICS

COMPANION WEBSITE

MATLAB[®] Exercises (for Chapters 1-14)

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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.

All listed MATLAB codes and parts of codes may be used only for educational purposes associated with the book.

*Branislav M. Notaroš
Fort Collins, Colorado*

LIST OF MATLAB EXERCISES IN ELECTROMAGNETICS

M1 **MATLAB EXERCISES** Electrostatic Field in Free Space

1

Section 1.1 Coulomb's Law

ME 1.1 Vector magnitude. (function `vectorMag.m`) **TUTORIAL**

ME 1.2 2-D vector plot. (function `vecPlot2D.m`) **HINT**

ME 1.3 3-D vector plot. (function `vecPlot3D.m`) **TUTORIAL**

ME 1.4 Electric force due to multiple charges. **TUTORIAL**

ME 1.5 Four charges at tetrahedron vertices. **HINT**

ME 1.6 Three point charges in Cartesian coordinate system. **HINT**

Section 1.2 Definition of the Electric Field Intensity Vector

ME 1.7 Electric field due to multiple charges.

ME 1.8 Three charges at rectangle vertices. **HINT**

Section 1.5 Electric Field Intensity Vector Due to Given Charge Distributions

ME 1.9 Charged ring. **HINT**

ME 1.10 Symbolic integration. (function `integral.m`)

ME 1.11 Charged disk. **TUTORIAL**

ME 1.12 Charged hemisphere, numerical integration. **HINT**

ME 1.13 Vector numerical integration and field visualization using `quiver`. **TUTORIAL**

ME 1.14 Visualization of the electric field due to four point charges. **HINT**

ME 1.15 Another field visualization using `quiver`.

ME 1.16 Fields due to line charges of finite and infinite lengths. **HINT**

Section 1.6 Definition of the Electric Scalar Potential

ME 1.17 Dot product of two vectors. (function `dotProduct.m`)

ME 1.18 Numerical integration of a line integral. (function `LineIntegral.m`)

ME 1.19 Work in the field of a point charge. **TUTORIAL**

ME 1.20 Numerical proof that E-field is conservative – movie. **TUTORIAL**

ME 1.21 Circulation of E-vector along a contour of complex shape.

Section 1.7 Electric Potential Due to Given Charge Distributions

ME 1.22 Electric potential due to multiple charges. **HINT**

ME 1.23 Electric potential due to a charged ring.

Section 1.10 Gradient

ME 1.24 Cartesian to cylindrical coordinate conversion. (function `car2Cyl.m`)

ME 1.25 Cylindrical to Cartesian coordinate conversion. (function `cy12Car.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 `cy12Sph.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 1.53 Field computation in postprocessing of the MoM solution. (function fieldE.m) **HINT**

ME 1.54 Field computation in plate and cube problems.

M2 **MATLAB EXERCISES** Dielectrics, Capacitance, and Electric Energy **30**

Section 2.4 Evaluation of the Electric Field and Potential Due to Polarized Dielectrics

ME 2.1 Uniformly polarized dielectric sphere, symbolic integration. **HINT**

ME 2.2 Nonuniformly polarized dielectric sphere, symbolic divergence.

ME 2.3 Nonuniformly polarized large dielectric slab.

ME 2.4 Numerical differentiation and integration in spherical coordinates. **TUTORIAL**

Section 2.6 Characterization of Dielectric Materials

ME 2.5 GUI – pop-up menu for the permittivity table of materials. (function function RelPermittivity.m) **TUTORIAL**

ME 2.6 Permittivity tensor of an anisotropic medium.

ME 2.7 GUI for the dielectric-strength table of materials. (function function DieStrength.m)

Section 2.9 Dielectric-Dielectric Boundary Conditions

ME 2.8 Dielectric-dielectric boundary conditions, oblique plane. **TUTORIAL**

ME 2.9 Oblique boundary plane with nonzero surface charge.

ME 2.10 Horizontal charge-free boundary plane.

ME 2.11 Horizontal boundary plane with surface charge.

ME 2.12 Vertical charge-free boundary plane.

ME 2.13 MATLAB computations of boundary conditions.

Section 2.10 Poisson's and Laplace's Equations

ME 2.14 Symbolic Laplacian in Cartesian coordinates. (function LaplaceCar.m)

ME 2.15 Symbolic Laplacian in cylindrical coordinates. (function LaplaceCyl.m)

ME 2.16 Symbolic Laplacian in spherical coordinates. (function LaplaceSph.m)

Section 2.11 Finite-Difference Method for Numerical Solution of Laplace's Equation

ME 2.17 FD-based MATLAB code – iterative solution. **TUTORIAL**

ME 2.18 Computation of matrices for a direct FD method. (function mACfd.m) **TUTORIAL**

ME 2.19 FD-based MATLAB code – direct solution. **TUTORIAL**

Section 2.13 Analysis of Capacitors with Homogeneous Dielectrics

ME 2.20 Capacitance calculator and GUI for multiple structures. (function function capCalc1.m) **TUTORIAL**

ME 2.21 RG-55/U coaxial cable and thundercloud capacitor.

ME 2.22 Capacitance calculator for wire transmission lines. (function `function capCalc2.m`)

ME 2.23 Capacitance of a metallic cube, using MoM MATLAB code. TUTORIAL

ME 2.24 Capacitance computation using FD MATLAB codes. TUTORIAL

ME 2.25 Main MoM matrix for a parallel-plate capacitor. (function `matrixACap.m`) TUTORIAL

ME 2.26 MoM analysis of a parallel-plate capacitor in MATLAB. TUTORIAL

Section 2.14 Analysis of Capacitors with Inhomogeneous Dielectrics

ME 2.27 GUI for capacitors with inhomogeneous dielectrics. (function `function capCalc3.m`)

ME 2.28 Symbolic and numerical integration and differentiation.

Section 2.17 Dielectric Breakdown in Electrostatic Systems

ME 2.29 Breakdown in a spherical capacitor with a multilayer dielectric. TUTORIAL

ME 2.30 Breakdown in a coaxial cable with a multilayer dielectric.

ME 2.31 Parallel-plate capacitor with multiple layers.

ME 2.32 Parallel-plate capacitor with multiple sectors.

M3 MATLAB EXERCISES Steady Electric Currents

55

Section 3.2 Conductivity and Ohm's Law in Local Form

ME 3.1 GUI for the conductivity table of materials. (function `Conductivity.m`)

ME 3.2 Temperature dependence of resistivity.

Section 3.5 Boundary Conditions for Steady Currents

ME 3.3 Conductor-conductor boundary conditions. HINT

ME 3.4 Law of refraction of current streamlines.

Section 3.7 Relaxation Time

ME 3.5 Relaxation time.

ME 3.6 Redistribution of charge in mica.

Section 3.8 Resistance, Ohm's Law, and Joule's Law

ME 3.7 Resistances of resistors with uniform cross sections. (function `resistance.m`)

ME 3.8 Multiple resistors in series. (function `resistorsInSeries.m`)

ME 3.9 Multiple resistors in parallel. (function `resistorsInParallel.m`)

ME 3.10 Two resistors with two cuboidal parts. HINT

Section 3.10 External Electric Energy Volume Sources and Generators

ME 3.11 Graphical and numerical solutions for a nonlinear circuit. TUTORIAL

Section 3.11 Analysis of Capacitors with Imperfect Inhomogeneous Dielectrics

ME 3.12 Conductance calculator for nonideal capacitors.

ME 3.13 2-D vector plots of volume current and field. **TUTORIAL**

ME 3.14 3-D plot of surface currents over a spherical electrode. **TUTORIAL**

Section 3.12 Analysis of Lossy Transmission Lines with Steady Currents

ME 3.15 Lossy two-wire lines with and without dielectric coatings. (function `conductanceTwoWireLine.m`)

ME 3.16 Conductance calculator and GUI. (function `conductanceCap.m`) **HINT**

M4 **MATLAB EXERCISES** Magnetostatic Field in Free Space

65

Section 4.1 Magnetic Force and Magnetic Flux Density Vector

ME 4.1 Cross product of two vectors. (function `crossProduct.m`) **TUTORIAL**

ME 4.2 Magnetic force between two moving point charges. **TUTORIAL**

ME 4.3 Magnetic flux density vector due to a moving charge.

ME 4.4 Magnetic field due to multiple moving charges. **HINT**

ME 4.5 3-D distribution of the magnetic field of a moving electron. **TUTORIAL**

ME 4.6 Magnetic field of a horizontally moving electron.

Section 4.3 Magnetic Flux Density Vector Due to Given Current Distributions

ME 4.7 Magnetic field of a finite straight wire conductor. (function `Bwireline.m`)

ME 4.8 Triangular current loop.

ME 4.9 Function to generate a 3-D plot of a circle. (function `circle.m`) **TUTORIAL**

ME 4.10 3-D visualization of magnetic field lines. **TUTORIAL**

ME 4.11 Circular surface current distribution, symbolic integration. **TUTORIAL**

ME 4.12 Disk with circular surface current of constant density.

ME 4.13 Magnetic field of a finite solenoid. (function `BzFiniteSolenoid.m`)

ME 4.14 Field plots for different length-to-diameter ratios.

ME 4.15 Magnetic field of an infinitely long strip conductor. (function `Binfstrip.m`)

ME 4.16 Two parallel strips with opposite currents.

Section 4.5 Applications of Ampère's Law

ME 4.17 Magnetic field of a cylindrical conductor.

ME 4.18 Magnetic field of a triaxial cable. **HINT**

ME 4.19 Visualization of the B-vector using quiver. **TUTORIAL**

ME 4.20 Field visualization by quiver for a hollow conductor.

ME 4.21 Field visualization by quiver for a triaxial cable.

Section 4.7 Curl

ME 4.22 Symbolic curl in Cartesian coordinates. (function `curlCar.m`)

ME 4.23 Symbolic curl in cylindrical coordinates. (function `curlCyl.m`)

ME 4.24 Symbolic curl in spherical coordinates. (function `curlSph.m`)

ME 4.25 Ampère's law in differential form.

Section 4.9 Magnetic Vector Potential

ME 4.26 Magnetic flux density from vector potential.

Section 4.11 Magnetic Dipole

ME 4.27 Magnetic dipole potential function. (function `magDipoleA.m`)

ME 4.28 Magnetic dipole field function. (function `magDipoleB.m`)

ME 4.29 A and B computation for a magnetic dipole.

ME 4.30 B from A for a magnetic dipole, symbolic differentiation.

ME 4.31 Visualization of the magnetic dipole potential using quiver. **HINT**

Section 4.12 The Lorentz Force and Hall Effect

ME 4.32 Electron travel in a uniform magnetic field – movie. **TUTORIAL**

M5 **MATLAB EXERCISES** Magnetostatic Field in Material Media

85

Section 5.3 Magnetization Volume and Surface Current Densities

ME 5.1 Nonuniformly magnetized ferromagnetic cube. **TUTORIAL**

ME 5.2 Uniformly magnetized material.

ME 5.3 Nonuniformly magnetized parallelepiped.

ME 5.4 Numerical and symbolic differentiation in cylindrical coordinates. **TUTORIAL**

ME 5.5 Infinite cylinder with circular magnetization.

ME 5.6 Symbolic solution for surface magnetization current.

ME 5.7 Visualization of the magnetization current using quiver. **HINT**

Section 5.4 Generalized Ampère's Law

ME 5.8 Total (conduction plus magnetization) current density.

Section 5.5 Permeability of Magnetic Materials

ME 5.9 GUI for the permeability table of materials. (function `RelPermeability.m`)

ME 5.10 Permeability tensor of an anisotropic medium.

ME 5.11 Inverse of the permeability tensor. **HINT**

Section 5.6 Maxwell's Equations and Boundary Conditions for the Magnetostatic Field

ME 5.12 Magnetic-magnetic boundary conditions, oblique plane. **HINT**

ME 5.13 Horizontal current-free boundary plane.

ME 5.14 Horizontal boundary plane with surface current.

ME 5.15 Vertical current-free boundary plane.

ME 5.16 MATLAB computations of magnetic boundary conditions. **HINT**

ME 5.17 Law of refraction of magnetic field lines.

Section 5.10 Kirchoff's Laws for Magnetic Circuits

ME 5.18 Generation of a linearized initial magnetization curve. (function magCurveSat.m)

ME 5.19 Numerical solution for a complex nonlinear magnetic circuit. **TUTORIAL**

ME 5.20 General numerical solution for the operating point. (function magCurveSolution.m)
TUTORIAL

ME 5.21 Simple nonlinear magnetic circuit with an air gap. **HINT**

ME 5.22 Another simple nonlinear magnetic circuit. **HINT**

ME 5.23 Magnetization-demagnetization – numerical solution and movie. **TUTORIAL**

ME 5.24 Movie with two magnetization-demagnetization curves.

M6 **MATLAB EXERCISES** Slowly Time-Varying Electromagnetic Field 100

Section 6.1 Induced Electric Field Intensity Vector

ME 6.1 Check if a time-harmonic field is low-frequency. (function slowlyTimeVaryingField.m)
TUTORIAL

ME 6.2 Low-frequency verification for three structures.

ME 6.3 Time lag and period plots vs. frequency.

ME 6.4 Induced electric field of a straight conductor – movie. **TUTORIAL**

Section 6.5 Computation of Transformer Induction

ME 6.5 Transformer emf, symbolic integration and differentiation. **TUTORIAL**

ME 6.6 Induced electric field of a solenoid – 2-D movie. **HINT**

ME 6.7 Fields of a solenoid – 3-D movie. **TUTORIAL**

ME 6.8 Generation of a hysteresis loop. (function hysteresis.m) **TUTORIAL**

ME 6.9 Finding B in time from H in time and a hysteresis loop. (function BinTime.m)
TUTORIAL

ME 6.10 Induced emf in a coil with a nonlinear core, numerical solution. **TUTORIAL**

ME 6.11 Nonlinear core, time-harmonic H-field, numerical solution.

Section 6.6 Electromagnetic Induction Due to Motion

ME 6.12 Motional emf, symbolic integration and differentiation.

Section 6.7 Total Electromagnetic Induction

ME 6.13 Transformer, motional, and total emf's in a moving contour. **HINT**

ME 6.14 Transformer, motional, and total emf's in a rotating loop.

ME 6.15 Rotating magnetic field – movie. **TUTORIAL**

ME 6.16 Rotating loop in a time-harmonic magnetic field – 3-D movie. **TUTORIAL**

ME 6.17 Rotating loop near an infinite ac line current – 2-D movie. **TUTORIAL**

Section 6.8 Eddy Currents

ME 6.18 Eddy currents in a thin conducting disk – 2-D movie. **HINT**

ME 6.19 Loss power due to eddy currents, symbolic integration.

M7 **MATLAB EXERCISES** Inductance and Magnetic Energy

118

Section 7.1 Self-Inductance

ME 7.1 Inductance calculator and GUI. (function indCalc.m) **HINT**

ME 7.2 P.u.l. inductance calculator for transmission lines. (function extInductCalc.m) **HINT**

Section 7.2 Mutual Inductance

ME 7.3 Mutual inductance p.u.l. of two two-wire lines. (function mutualIndTwoLines.m)

ME 7.4 Mutual inductance between phone and power lines. (function phoneLinePowerLine.m)

Section 7.3 Analysis of Magnetically Coupled Circuits

ME 7.5 Two coupled inductors connected in series. (function equInductanceSeries.m)

ME 7.6 Coupled inductors in parallel. (function equInductanceParallel.m)

ME 7.7 Equivalent input inductance of structures with coupled coils.

Section 7.5 Magnetic Energy Density

ME 7.8 Magnetic energy density, nonlinear material. (function magEnergyDensity.m)
TUTORIAL

ME 7.9 Energy of a nonlinear magnetic circuit – movie. **TUTORIAL**

ME 7.10 Energy of a nonlinear magnetic circuit with three branches.

ME 7.11 Energy of another nonlinear magnetic circuit.

ME 7.12 Energy lost in magnetization and demagnetization – movie. **HINT**

ME 7.13 Time-average power of hysteresis losses in a core.

Section 7.6 Internal and External Inductance in Terms of Magnetic Energy

ME 7.14 Internal inductance p.u.l. of a coaxial cable. (function `inductancesCoaxialCable.m`)

M8 MATLAB EXERCISES Rapidly Time-Varying Electromagnetic Field 127

Section 8.1 Displacement Current

ME 8.1 Time-harmonic magnetic field in a nonideal capacitor – 2-D movie. **HINT**

ME 8.2 3-D plot of the instantaneous magnetic field intensity. **HINT**

ME 8.3 Conduction to displacement current ratio. (function `condDispCurrentRatio.m`)

ME 8.4 Current ratio plot vs. frequency for rural ground. **HINT**

ME 8.5 Current ratio plots for fresh water and seawater.

Section 8.2 Maxwell's Equations for the Rapidly Time-Varying Electromagnetic Field

ME 8.6 Maxwell's equations, symbolic differentiation and integration. (function `diffMaxwellFirstEq.m`) **TUTORIAL**

ME 8.7 Magnetic from electric field of an antenna, symbolic computation. **HINT**

Section 8.4 Boundary Conditions for the Rapidly Time-Varying Electromagnetic Field

ME 8.8 PEC boundary conditions, plot of surface currents. **TUTORIAL**

ME 8.9 PEC boundary conditions, movie of surface charges. **TUTORIAL**

Section 8.5 Different Forms of the Continuity Equation for Rapidly Time-Varying Currents

ME 8.10 Current and charge distributions over a circular plate. **HINT**

Section 8.6 Time-Harmonic Electromagnetics

ME 8.11 Symbolic rms value of a periodic signal. (function `rmsValue.m`)

Section 8.7 Complex Representatives of Time-Harmonic Field and Circuit Quantities

ME 8.12 Finding the phase of a complex number. (function `phaseDeg.m`) **HINT**

ME 8.13 Graphical representation of complex numbers. (function `cplxNumPlot.m`) **TUTORIAL**

ME 8.14 Graphical representation of complex voltage and current.

ME 8.15 Movie of voltage phasor rotation in complex plane. **TUTORIAL**

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

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ME 13.11 Magnetic field components of an arbitrary TE mode. (functions `HxTE.m`, `HyTE.m`, and `HzTE.m`)

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ME 13.44 Symbolic computation of energy, dominant cavity mode. **TUTORIAL**

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ME 14.15 Radiation and ohmic resistances of a nonloaded short dipole.

ME 14.16 Radiation efficiency of a short dipole with cosine current. **HINT**

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ME 14.46 Full-wave interelement spacing and grating lobes.

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ME 14.50 Visualization of the pattern multiplication theorem. (function `patternMultiplication.m`) **TUTORIAL**

ME 14.51 Array of two collinear Hertzian dipoles – pattern multiplication. **TUTORIAL**

ME 14.52 Array of two parallel dipoles – pattern multiplication. **HINT**

ME 14.53 Nonuniform array of three parallel half-wave dipoles. **HINT**

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