ELECTROMAGNETICS FOR ENGINEERS

ARLON T. ADAMS

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RECTANGULAR COORDINATES

$$\nabla\psi = \frac{\partial\psi}{\partial x}\,\hat{\mathbf{x}} + \frac{\partial\psi}{\partial y}\,\hat{\mathbf{y}} + \frac{\partial\psi}{\partial z}\,\hat{\mathbf{z}}$$

$$\nabla\cdot\mathbf{F} = \frac{\partial F_x}{\partial x} + \frac{\partial F_y}{\partial y} + \frac{\partial F_z}{\partial z}$$

$$\nabla\times\mathbf{F} = \left[\frac{\partial F_z}{\partial y} - \frac{\partial F_y}{\partial z}\right]\hat{\mathbf{x}} + \left[\frac{\partial F_x}{\partial z} - \frac{\partial F_z}{\partial x}\right]\hat{\mathbf{y}}$$

$$+ \left[\frac{\partial F_y}{\partial x} - \frac{\partial F_x}{\partial y}\right]\hat{\mathbf{z}}$$

CYLINDRICAL COORDINATES

$$\nabla\psi = \frac{\partial\psi}{\partial r}\,\hat{\mathbf{r}} + \frac{1}{r}\frac{\partial\psi}{\partial\phi}\,\hat{\boldsymbol{\phi}} + \frac{\partial\psi}{\partial z}\,\hat{\mathbf{z}}$$

$$\nabla\cdot\mathbf{F} = \frac{1}{r}\frac{\partial}{\partial r}(rF_r) + \frac{1}{r}\frac{\partial F_\phi}{\partial\phi} + \frac{\partial F_z}{\partial z}$$

$$\nabla\times\mathbf{F} = \left[\frac{1}{r}\frac{\partial F_z}{\partial\phi} - \frac{\partial F_\phi}{\partial z}\right]\hat{\mathbf{r}} + \left[\frac{\partial F_r}{\partial z} - \frac{\partial F_z}{\partial r}\right]\hat{\boldsymbol{\phi}}$$

$$+ \left[\frac{1}{r}\frac{\partial}{\partial r}(rF_\phi) - \frac{1}{r}\frac{\partial F_r}{\partial\phi}\right]\hat{\mathbf{z}}$$

SPHERICAL COORDINATES

$$\nabla\psi = \frac{\partial\psi}{\partial r}\,\hat{\mathbf{r}} + \frac{1}{r}\frac{\partial\psi}{\partial\theta}\,\hat{\boldsymbol{\theta}} + \frac{1}{\mathrm{r}\sin\theta}\frac{\partial\psi}{\partial\phi}\,\hat{\boldsymbol{\phi}}$$

$$\nabla\cdot\mathbf{F} = \frac{1}{r^2}\frac{\partial}{\partial r}(r^2F_r) + \frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}(F_\theta\sin\theta)$$

$$+ \frac{1}{r\sin\theta}\frac{\partial F_\phi}{\partial\phi}$$

$$\nabla\times\mathbf{F} = \frac{1}{r\sin\theta}\left[\frac{\partial}{\partial\theta}(F_\phi\sin\theta) - \frac{\partial F_\theta}{\partial\phi}\right]\hat{\mathbf{r}}$$

$$+ \frac{1}{r}\left[\frac{1}{\sin\theta}\frac{\partial F_r}{\partial\phi} - \frac{\partial}{\partial r}(rF_\phi)\right]\hat{\boldsymbol{\theta}}$$

$$+ \frac{1}{r}\left[\frac{\partial}{\partial r}(rF_\phi) - \frac{\partial F_r}{\partial\theta}\right]\hat{\boldsymbol{\phi}}$$

Arlon T. Adams, Ph.D., University of Michigan, is Associate Professor of Electrical Engineering at Syracuse University. Prior to his teaching appointment Dr. Adams was an engineer with the Sperry Gyroscope Company. His research interests are in antennas and microwaves and he has published extensively in those areas. Dr. Adams is a consultant to the Syracuse University Research Corporation.

To my mother,
Ruth Whipple

Preface

This textbook is intended for the introductory course in electromagnetic fields for students of engineering. The text is divided into five parts, covering vector analysis, electrostatics, magnetostatics, Faraday's Law and material characteristics, and Maxwell's Equations. Wherever possible, the approach is to appeal to the student's physical intuition, and to this end a large number of illustrations is provided. Special features include a chapter on computer solution of electrostatic problems, emphasizing matrix inversion methods, and one on the characteristics of dielectric and magnetic materials. The text contains more than enough material for a one semester course. Numerous problems are given at the end of each chapter, with the more difficult problems indicated by a dagger.

After a survey of the applications of electromagnetic theory, Part I presents the vector concepts of curl, divergence, and gradient in terms of the limiting integral definitions which yield useful physical insights. Physical pictures, such as the divergence meter and the curl meter, are emphasized. Appendix D is a useful adjunct to this chapter, introducing a shorthand notation which leads to the generalized divergence theorem and the generalized Stokes' Law.

In Part II the basic laws of electrostatics are derived by inductive logic rather than by the usual approach of starting with Coulomb's Law. Thus the curl and divergence properties of the electrostatic field, rather than the inverse-square behavior of charges, are emphasized. The discussion of dielectrics emphasizes the drift of bound charges, which results in polarization. Perhaps more emphasis than usual is placed upon the parallel role of the bound, free, and total charge sources. In the discussion of approximate methods the emphasis is on the matrix inversion techniques for electrostatic problems. Examples are given and computer programs for the examples are provided in Appendix E. The problems and examples in this chapter might offer material for term projects.

After introducing the theory of magnetism, Part III further unifies the concepts of vector analysis by introducing Helmholtz's Theorem, and emphasizes that in electrostatics and magnetostatics we have really been studying the general properties of curlfree and divergenceless vector fields, respectively.

Faraday's experiments are described in abbreviated form, in Part IV, leading up to a statement of Faraday's Law. Some of the effects of motion are discussed in terms of a new electric field E' measured by a moving observer. Voltage is redefined in terms of E' and numerous examples are given. A descriptive account of the characteristics of dielectric and magnetic materials is given.

In Part V the subject of Maxwell's equations is approached from several points of view, thereby providing complete justification for the second curl equation.

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ARLON T. ADAMS

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VECTOR IDENTITIES

$$\mathbf{A} \times (\mathbf{B} \times \mathbf{C}) = \mathbf{B}(\mathbf{A} \cdot \mathbf{C}) - \mathbf{C}(\mathbf{A} \cdot \mathbf{B})$$

$$\nabla(\psi\phi) = \phi\nabla\psi + \psi\nabla\phi$$

$$\nabla \cdot (\psi\mathbf{A}) = \nabla\psi \cdot \mathbf{A} + \psi(\nabla \cdot \mathbf{A})$$

$$\nabla \times (\psi\mathbf{A}) = \nabla\psi \times \mathbf{A} + \psi(\nabla \times \mathbf{A})$$

$$\nabla \cdot (\mathbf{A} \times \mathbf{B}) = \mathbf{B} \cdot (\nabla \times \mathbf{A}) - \mathbf{A} \cdot (\nabla \times \mathbf{B})$$

$$\nabla \cdot (\nabla \times \mathbf{A}) = 0$$

$$\nabla \times (\nabla V) = 0$$

$$\nabla \times \nabla \times \mathbf{A} = \nabla(\nabla \cdot \mathbf{A}) - \nabla^2\mathbf{A}$$

THE GENERALIZED DIVERGENCE THEOREM AND THE GENERALIZED STOKES' LAW

$$\iiint_v \nabla \circledast F \, dv = \oiint_s \hat{\mathbf{n}} \circledast F \, ds$$

$$\iint_s (\hat{\mathbf{n}} \times \nabla) \circledast F \, ds = \oint_c d\mathbf{l} \circledast F$$

Divergence Theorem: $\iiint_v \nabla \cdot \mathbf{F} \, dv = \oiint_s \mathbf{F} \cdot \hat{\mathbf{n}} \, ds$

Stokes Law: $\iint_s \nabla \times \mathbf{F} \cdot \hat{\mathbf{n}} \, ds = \oint_c \mathbf{F} \cdot d\mathbf{l}$

GAUSS' LAW

$$\nabla \cdot \mathbf{D} = \rho$$

$$\oiint \mathbf{D} \cdot \hat{\mathbf{n}}\, ds = q_{\text{encl}} = \iiint \rho\, dv$$

AMPERE'S LAW

$$\nabla \times \mathbf{H} = \mathbf{J}$$

$$\oint \mathbf{H} \cdot \mathbf{dl} = I_{\text{encl}} = \iint \mathbf{J} \cdot \hat{\mathbf{n}}\, ds$$

FARADAY'S LAW

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$V_{ab} = -\frac{d}{dt} \iint_s \mathbf{B} \cdot \hat{\mathbf{n}}\, ds$$

$$= -\iint_s \frac{\partial \mathbf{B}}{\partial t} \cdot \hat{\mathbf{n}}\, ds + \oint_c \mathbf{v} \times \mathbf{B} \cdot \mathbf{dl}$$

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