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Foreword

System-level electromagnetic compatibility (EMC) design is one of the core technologies in the research and development of large-scale platform. With the increasingly harsh electromagnetic environment and increasingly complex electronic systems on large platforms, system-level EMC quantitative design becomes a very important methodology in great demand.

This book is based on the research and engineering practice of Prof. Donglin Su and the EMC Research Team in Beihang University which she has led for about 30 years. The book starts with an introduction of the basic EMC theories and the basic concept of system-level EMC quantitative design. Then, combined with the experience in aircraft EMC performance analysis, engineering design, and troubleshooting, the book discusses the key technologies in the quantitative design of system-level EMC. Next, taking the aircraft system-level EMC design as an example, the authors introduce the method of quantitative design and evaluation of system-level EMC. Evaluation and quality control methodologies of EMC are also discussed from the perspective of lifecycle EMC performance. The authors then discuss the common problems and solutions of CE102, RE102, and RS103 tests. This book is the first academic monograph about system-level EMC quantitative design theory and method in China. I hope the book will provide good guidance to the readers in both theory and applications.

Professor Donglin Su has a great enthusiasm for aviation and EMC. She has devoted herself to the theoretical research and engineering practice in system-level quantitative design of EMC for 30 years, and she has made a significant achievement in this field. She is the leading expert in EMC quantitative design with outstanding contributions to the development of the EMC industry. She is the recipient of the Second Prize of the State Science and Technology Progress Awards of China with her theory and method of “top-down quantitative design of system-level EMC for aircraft." This achievement is a major innovation to solve the system-level EMC issues and plays an important role in the successful development of aircraft.

I believe the publication of this book will greatly promote the development of China's EMC field.

Shijiazhuang, Hebei, China
Liu Shanghe
Academician of Chinese Engineering Academy

Preface

Aircraft, satellites, ships, and electronic information systems are large and complex information platforms. Their EMC demonstration and design at system level (also known as platform level) have always been a universal problem. There are two main causes of the problem: One is the lack of design standard; the other is the lack of demonstration and design methodologies. These two might also be the major reasons why EMC is difficult to include in the demonstration and design of most large-scale complex information systems and platforms.

High quality of EMC is a result of design.

"System-level EMC quantitative technology" was proposed by the EMC Research Team of Beihang University, China. There are more than a hundred of teachers, students, and engineering technicians in the team. This book covers our analysis of the advanced experience and achievements of EMC research both at home and abroad, as well as our own research on theories and methodologies of EMC and relevant disciplines. The book also reflects our experience from more than 20 cases of system-level EMC design and troubleshooting and our unremitting efforts in the field of EMC in the past 30 years. I hope this book will serve as a good reference to researchers and engineers in EMC and relevant field in China.

We are sincerely grateful to the great opportunity created by China's national defense and aviation industry. We would also like to thank Beihang University for the excellent platform it provides for our careers.

The EMC Research Team of Beihang University has been supported by authorities at all levels and by other research institutes and manufacturers. We have also benefited enormously from ideas and discussions with experts in EMC and related fields at home and abroad. We would like to gratefully acknowledge all of the people who helped us write this book.

The research work covered in this book has been supported by the Key Program, General Program, and Young Scientist Fund of the National Natural Science Foundation of China as well as the National Defense Fund and Aviation Fund.

This book is divided into two parts: Part I introduces the basic theories of system-level EMC quantitative design, including electromagnetic field and electromagnetic wave, microwave technology, and antenna principle. Part II focuses on the system-level EMC quantitative design, including basic concepts, theoretical methods, major technological solutions, EMC quality control and evaluation methods, software, and application cases.

Professor Donglin Su is the corresponding author of this book; Prof. Shuguo Xie wrote the chapter of antenna theories; the part of test requirements and indicators was written by Assoc. Prof. Fei Dai; the EMC quantitative design application cases were written by Dr. Yan Liu; EMC quality control application cases were written by Dr. Yunfeng Jia. The preparation of this book has also been assisted by other members of the EMC Research Team of Beihang University, to whom we would like to express our gratitude for their hard work.

Special thanks to Academician Liu Shanghe, Academician Zhang Minggao, and Prof. Wang Junhong who have recommended the book.

Finally, I would like to express my heartfelt thanks to the National Defense Industry Press, which supports the publication of this book.

We welcome our readers to point out if there are any errors or mistakes in this book.

Beijing, China

Donglin Su
Shuguo Xie
Fei Dai
Yan Liu
Yunfeng Jia

Contents

Part I Electromagnetic Compatibility Fundamental Theories

Part II Methods and Applications of Quantitative System-Level EMC Design

Symbols

B	System bandwidth (Hz)
B_R	Transmitter bandwidth (Hz)
B_T	Receiver bandwidth (Hz)
C	Capacitance (F)
D_r	Maximum size of the receiving antenna (equivalent diameter) (m)
D_t	Maximum size of the transmitting antenna (equivalent diameter) (m)
$D(\theta, \phi)$	Power gain (dB)
$\boldsymbol{E}$	Electric field strength (V/m)
E_{mn}	Electric field strength of mode m, n (V/m)
$EMC(s)$	EMC condition
$\tilde{\mathbf{E}}$	Complex electric field vector (V/m)
$E(\Theta, \Phi, t, f)$	Environmental electromagnetic interference source model
$\mathbf{F}$	Force (N)
F	Total noise figure (dB)
FIM	Fundamental inference margin (dB)
$F(\theta, \varphi)$	Directivity function
G	Conductance (S)
G	Total gain (dB)
$G_r(\theta_r, \varphi_r)$	Receiving antenna gain in the transmitting direction (dB)
$G_r(f_{in})$	Power gain of the receiving antenna (dB)
G_{sat}	Gain compression at the saturation point (dB)
$G_t(\theta_t, \varphi_t)$	Transmitting antenna gain in the receiving direction (dB)
$G_t(f_{in})$	Power gain of the transmitting antenna (dB)
$\boldsymbol{H}$	Magnetic field strength (A/m)
$H_{m,n}$	Magnetic field strength of mode m, n (A/m)
$\tilde{\mathbf{H}}$	Complex magnetic field vector (A/m)
$H(\Theta, \Phi, t, f)$	Interference coupling path model
$\boldsymbol{I}$	Linear current (A)
$I(E, \mathrm{R}; f)$	Isolation matrix
$\mathbf{I}_{\mathrm{limit}}(\mathrm{dB})$	Isolation safety margin (dB)

$I(t,f)$	Safety margin function
$\dot{I}$	Current vector (A)
$\boldsymbol{J}$	Volume current (A/m^2)
J_A	Interference power matrix (dBm)
$\boldsymbol{K}$	Surface current (A/m)
L	Inductance (H)
L	Isolation (dB)
L_a	Antenna isolation (dB)
L_d	Spatial isolation (dB)
L_P	Loss caused by the polarization mismatch (dB)
$\boldsymbol{L_{rB}}$	Reception suppression matrix of the receivers at the analysis frequency point (dB)
$\boldsymbol{L_{rf}}$	Receiving feeder loss matrix of the receivers (dB)
$\boldsymbol{L_{tB}}$	Emission attenuation matrix of the transmitters at the analysis frequency (dB)
$\boldsymbol{L_{tf}}$	Transmitting feeder loss matrix of the transmitter (dB)
M	Mutual inductance (H)
N_0	Noise power (dBm)
NMSE	Normalized mean square error (NMSE)
$O(\Theta, \Phi, t,f)$	Interference output model
P	Particle
$\mathrm{P}_{1\mathrm{dB}}$	Output power of the 1 dB gain compression point (dBm)
P_D	Desired signal level (dBm)
P_{IIP3}, P_{OIP3}	Input or output power of the TOI point (dBm)
P_{in}	Input power (dBm)
P_{out}	Output power (dBm)
P_{REF}	Reference signal level (dBm)
P_r	Receiving power (dBm)
P_{sat}	Output power of the saturation point (dBm)
$\boldsymbol{P_{smin}}$	Sensitivity matrix (dBm)
$\boldsymbol{P_t}$	Transmitting power matrix (dBm)
P_t	Transmitting power (dBm)
$\dot{P}_\Sigma$	Radiation power (dBm)
Q	Total charge (C)
Q_{net}	Net charge (C)
R	Resistance (Ω)
RIM	Receiver inference margin (dB)
R_Σ	Radiation resistance (Ω)
$\mathbf{S}$	Poynting vector (W/m^2)
S	Surface (m^2)
SIM	Spurious inference margin (dB)
$\boldsymbol{S_m}$	EMC safety margin matrix (dBm)
S/N	SNR matrix
$(S/N)_{REF}$	SNR of reference signal level (dB)

$\tilde{\mathbf{S}}$	Poynting complex vector (W/m^2)
$S(\Theta, \Phi, t, f)$	Susceptive subject model
T	Temperature (K)
T_A	Equivalent noise temperature (K)
$\boldsymbol{T_E}$	Transmitting conversion matrix
T_o	Temperature(290 K) (K)
$\boldsymbol{T_R}$	Receiving conversion matrix
TE	Transversal electric wave
TEM	Transversal electromagnetic wave
TE_{mn}	Transversal electric wave of mode m, n
TIM	Transmitter inference margin (dB)
TM	Transverse magnetic wave
TM_{mn}	Transverse magnetic wave of mode m, n
$T(\Theta, \Phi, t, f)$	Inference source model
V	Volume (m^3)
V	Voltage (V)
$\dot{V}$	Voltage vector (V)
VSWR	Voltage standing wave ratio
W	Total electromagnetic field energy (J)
W_E	Total electric field energy (J)
W_e	Total electromagnetic field energy in capacitor (J)
W_H	Total magnetic field power (J)
W_m	Total magnetic field energy in inductor (J)
X	Reactance (J)
Y	Admittance (S)
Z	Impedance (Ω)
Z_c	Characteristic impedance (Ω)
f	Frequency (Hz)
f_c	Cutoff frequency (Hz)
f_E	Transmitting of power of transmitter (Hz)
f_0	Central operating frequency of equipment (Hz)
f_R	Receiver response frequency, receiver central frequency (Hz)
f_T	Transmitter central frequency (Hz)
i	Transient current (A)
i_n	Unit vector in the normal direction of the boundary
$\mathbf{i}_{r_c}$	Unit vector in r_c direction on column coordinate system
$\mathbf{i}_{r_s}$	Unit vector in r_s direction on spherical coordinate system
$\boldsymbol{i}_v$	Unit vector in the flowing direction
$\mathbf{i}_x$	Unit vector in x-axis of Cartesian coordinate system
$\mathbf{i}_y$	Unit vector in y-axis of Cartesian coordinate system
$\mathbf{i}_z$	Unit vector in z-axis of Cartesian or column coordinate system
$\mathbf{i}_\theta$	Unit vector in θ-axis of spherical coordinate system
$\mathbf{i}_\varphi$	Unit vector in φ-axis of column or spherical coordinate system
k	Free space phase constant (Rad/m)

k_c	Cutoff wave number (Rad/m)
$(k_c)_{mn}$	Cutoff wave number in m, n mode (Rad/m)
m, n	Various modes that can exist in the waveguide
p_d	Electromagnetic power density of the loss in the resistance bar (W/Ω)
q	Point charge (C)
$\boldsymbol{r}$	Radius vector of spatial point (M)
r_C	r_c-coordinate on column coordinate system (M)
$\boldsymbol{r}_P$	Radius vector of the position where charge P locates (M)
r_s	r_s coordinate on spherical coordinate system (M)
t	Time (s)
$\boldsymbol{\upsilon}$	Velocity (m/s)
v	Transient voltage (V)
w	Electromagnetic field energy density (J/m^3)
w_E	Electric field energy density (J/m^3)
w_H	Magnetic field energy density (J/m^3)
x	x-coordinate on Cartesian coordinate (M)
$x(k)$	System input
$x(t)$	System input
y	y-coordinate on Cartesian coordinate (M)
$y(k)$	System output
$y(t)$	System output
z	z-coordinate on Cartesian coordinate (M)
$d\boldsymbol{a}$	Surface element vector on surface S (m^2)
da	Surface element on surface S (m^2)
ds	Line element on curve C (M)
dV	Volume element in volume V (m^3)
α	Attenuation constant (dB/m)
β	Phase shift constant (Rad/m)
γ	Wave propagation constant
δ_e	Skin depth (M)
ε	Dielectric constant (F/m)
$\varepsilon_{0.}$	Vacuum dielectric constant: $1/36\pi \times 10^{-9}$ (F/m)
η	Surface charge (C/m^2)
η	Wave impedance (Ω)
η_0	Wave impedance in free space (Ω)
η_{TE}	TE wave impedance (Ω)
η_{TEM}	TEM wave impedance (Ω)
η_{TM}	TM wave impedance (Ω)
θ	θ-coordinate on spherical coordinate system (rad)
λ	Line charge (C/m)
λ	Wavelength (M)
λ_c	Cutoff wavelength (M)
$(\lambda_c)_{mn}$	Cutoff wavelength of mode m, n (M)

μ	Magnetic permeability (H/m)
μ_0	Magnetic permeability in vacuum: $4\pi \times 10^{-7}$ (H/m)
ρ	Volume charge (C/m^3)
ρ	Voltage standing wave ratio
σ	Conductivity (s/m)
Γ	Reflection coefficient
Φ	Potential (V)
φ	φ-coordinate on column coordinate or spherical coordinate system (rad)
ω	Angular frequency (rad/m)

Part I

Electromagnetic Compatibility Fundamental Theories

With the rapid development of electronic information technology, electromagnetic compatibility (EMC) involves more and more disciplines, such as electronic science and technology, information and communication engineering, control science, electrical appliances, power electronics, material science and engineering, and mechanical electronics. Especially with the wide application of radio frequency (RF) technology and high-rate digital technology, there are increasing number of EMC problems caused by the coupling channel composed of free space, the distributed parameter effect of metal conductor, the RF parasitic parameter of devices, the transmission line effect of metal apertures, etc. Therefore, in order to understand the basic principles of EMC, we first study the basic theories and principles of EMC including the theory of electromagnetic fields and waves, microwave engineering, and antenna theory.

This part introduces the fundamental theories and methods of EMC, namely electromagnetic fields and waves, microwave engineering, and antenna theory and engineering.

In the part of electromagnetic fields and waves, by introducing the overall physical meaning of Maxwell's equations, we explain that the characteristics of the electronic circuits under direct current (DC) or low frequency are essentially different from the characteristics under radio frequency or microwave. By analyzing the electromagnetic power flow, our readers will understand that the energy can be transmitted through the free space between the voltage source and the load even in the case of DC. By analyzing the reflection of electromagnetic waves, we illustrate that the tangential electric field of the ideal conductor surface is zero, which is called the electric wall. The electric wall does not have to be composed of ideal conductors, air can also be used for shielding instead (the grounded closed conductor shell, which can shield electric fields and electromagnetic fields, is a typical applications of metal electric walls. The high-speed digital connector is a typical application for air electric walls).

In the section of microwave engineering, by learning the transmission line theory, our readers will understand that the characteristics of the single-conductor and double-conductor transmission line involved in the case shielding, and the cross talk problem in the cable layout. We also explain that there is essential difference of electronic circuit characteristics between when the electronic circuit working in DC and when the linear degree of electronic circuit is comparable to the working wavelength.

In the section of antenna theory and engineering, by analyzing the field generated by the alternating electric dipole, we explain to our readers that after the airborne antenna being installed, its radiation characteristics may greatly change, which will further change the functional indicators of the airborne antenna, such as the working distance. Through this section, our readers will also understand that the system-level EMC design not only includes antenna layout design, but also involves the design of RF front-end part, feeder part, and baseband part.

Chapter 1
Electromagnetic Field and Wave

Field is a material form that exists objectively and may permeate the space, with a special law of motion. Field can vary with spatial position and time; i.e., the field parameters can be expressed as a function of space and time.

This chapter discusses the classical electromagnetic field theories [1], which only consider the macroscopic statistical electromagnetic field phenomenon, without consideration of the microscopic electromagnetic field and the quantum effects of the field. Therefore, the infinitesimal mentioned in the book is macroscopic, not mathematical.

This chapter is the basis of the entire book, and our readers need to understand the mathematical physical concepts in this chapter.

1.1 The Physical Meaning of Maxwell's Equations

Through the study of the overall physical meaning of Maxwell's equations, our readers will understand that the characteristics of the electronic circuits and system in DC and low frequency are essentially different than that in radio frequency (RF) and microwave.

To better explain the symbols of Maxwell's equations, we first define the source and field symbols used in this book, including the basic source parameters related to charge and current and the basic field parameters related to fields.

1.1.1 Basic Source Variables

The variables related to charge include point charge q, line charge λ, surface charge η, and volume charge ρ.

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(1) Point charge q, the unit is Coulomb (symbol: C): From a macroscopic point of view, if the charge distribution area is very small, it can be considered to be distributed only at one point. This kind of charge distribution is called a point charge distribution, and the electric quantity q is the point charge quantity. In general, the point charge is a function of time, i.e., $q(P) = q(\mathbf{r_P}, t)$, where $\mathbf{r_P}$ is the positional vector of the point where the point charge P is located.

(2) Line charge λ, the unit is Coulomb/meter (symbol: C/m): If the area of the charge distribution is very thin, its cross-sectional area can be considered to be zero from the macroscopic perspective. Such a charge distribution is called a line charge distribution, and the charge is distributed on a curve. For any point P on the curve, if the line element Δs containing point P has a charge amount Δq, when Δs shrinks to zero toward point P, the limit of the ratio of Δq to Δs is the line charge density of point P, i.e., $\lambda(\mathbf{P}) = \lim\limits_{\Delta s \to 0} \frac{\Delta q}{\Delta s}$. In general, the line charge is a function of time and space, i.e., $\lambda = \lambda(x, y, z, t) = \lambda(\mathbf{r}, t)$. For a curve C, the amount of charge on it should be $Q(t) = \int_c \lambda(\mathbf{r}, t)\mathrm{d}s$, where ds is the line element on curve C.

(3) Surface charge η, unit is Coulomb/meter^2 (symbol: C/m^2): If the region of the charge distribution is very thin, from a macroscopic point of view, the thickness is considered to be zero. Such a charge distribution is called a surface charge distribution, and these charges are distributed on a curved surface without volume. For any point P on the surface, if the area element Δa containing the point contains the charge amount Δq, when Δa shrinks toward point P and approaches zero, the limit of the ratio of Δq to Δa is the surface charge density $\eta(P)$ of point P, and $\eta(\mathbf{P}) = \lim\limits_{\Delta a \to 0(P)} \frac{\Delta q}{\Delta A}$. In general, the surface charge density is a function of spatial position and time, i.e., $\eta = \eta(x, y, z, t) = \eta(\mathbf{r}, t)$. For a surface S, the amount of charge on it should be $Q(t) = \int_S \eta(\mathbf{r}, t)\mathrm{d}a$, where d$a$ is the area element of surface S.

(4) Volume charge ρ, the unit is Coulomb/meter^3 (symbol: C/m^3): If the volume element ΔV containing any point P contains the charge amount Δq, when ΔV shrinks toward point P and approaches zero, the limit of the ratio of Δq to ΔV is the volume charge density, i.e., $\rho(P) = \lim\limits_{\Delta V \to 0(P)} \Delta q/\Delta V$. In general, the volume charge density can be a function of spatial position and time, i.e., $\rho = \rho(x, y, z, t) = \rho(\mathbf{r}, t)$, where r is the radius vector of the spatial point. For a known volume V, the amount of charge contained inside is $Q(t) = \int_V \rho(\mathbf{r}, t)\mathrm{d}V$, where d$V$ is the volume element of volume V.

The variables related to current are line current I, surface current K, and volume current J.

(1) Line current I, the unit is Ampere (symbol: A): If the area where the current goes through is very thin, from the macroscopic aspect, the area is considered to be a line with zero cross section. In this case, the current distribution can be considered as a line current with current I. In general, the line current is a function of space and time, i.e., $I = I(x, y, z, t) = I(\boldsymbol{r}, t)$.

(2) Surface current K, the unit is Ampere/meter (symbol: A/m): If the area which the current goes through is very thin, in a macroscopic ideal case, the current can be considered to flow on a curved surface. For a point P on the surface, if the flow direction of the current at point P is $\boldsymbol{i}_v$, the current flowing through the point P and the line element Δl perpendicular to $\boldsymbol{i}_v$ is ΔI, and the thickness of the surface $h \to 0$, then the surface current density at the point P is $\boldsymbol{K}(P) = i_v \lim_{\Delta l \to 0(P)} \Delta I / \Delta l$. In general, the surface current density is a function of spatial position and time, $\boldsymbol{K} = \boldsymbol{K}(x, y, z, t) = \boldsymbol{K}(\boldsymbol{r}, t)$. For a curve C on a surface with a surface current $K(\boldsymbol{r}, t)$, the current flowing through it should be $I(t) = \int_C \boldsymbol{K}(\boldsymbol{r}, t) \cdot i_{ns} ds$, where d$s$ is the line element on C and $\cdot\boldsymbol{i}_{ns}$ is the unit vector in the normal direction of the line element.

(3) Volume current $\boldsymbol{J}$, the unit is Ampere/meter^2 (symbol: A/m^2): For any point P in space, if the unit vector of the current in the flowing direction of point P is $\boldsymbol{i}_v$, and the current intensity flowing through the surface element Δa containing P point and perpendicular to $\boldsymbol{i}_v$ is ΔI, then the volume current density at point P is: $\boldsymbol{J}(P) = \boldsymbol{i}_v \underset{\Delta a \to 0(P)}{\boldsymbol{lim}} \Delta I / \Delta a$. In general, the volume current density is a function of spatial position and time, i.e., $\boldsymbol{J} = \boldsymbol{J}(x, y, z, t) = \boldsymbol{J}(\boldsymbol{r}, t)$. The total current flowing through a curved surface S is $\mathbf{I}(t) = \int_C J(\mathbf{r}, t) \cdot \mathrm{d}a$, where $\boldsymbol{da}$ is a vector surface element on S.

1.1.2 Basic Field Variables

(1) Lorentz force (F), the unit is Newton (symbol: N): Experiments have shown that a point charge q moving at velocity $\boldsymbol{v}$ is subjected to a force in the electromagnetic field in free space. The force can be written as $\boldsymbol{F} = q\boldsymbol{E} + q\boldsymbol{v} \times \mu_0 \boldsymbol{H}$. This formula is called Lorentz force formula, where μ_0 is the permeability of free space. The first part on the right side of the formula is independent of the speed of motion, and the second part is proportional to the speed and perpendicular to it.

(2) Electric field intensity E, the unit is Newton/Coulomb (symbol: N/C) or Volt/meter (symbol: V/m): The electric field intensity is defined by the portion of Lorentz force that is independent of speed, i.e., $\boldsymbol{E} = \boldsymbol{F}|_{v=0}/q$.

(3) Magnetic field intensity H, the unit is Ampere/meter (symbol: A/m): The magnetic field intensity is defined by the velocity-dependent part of Lorentz force formula. Let $\Delta \boldsymbol{F} = \boldsymbol{F} - q\boldsymbol{E} = \boldsymbol{F}|_{E=0}$, then $|\mathbf{H}| = |\Delta \mathbf{F}| / (\mu_0 |q| |\mathbf{v}| |\sin \alpha|)$, where α is the angle between $\boldsymbol{v}$ and $\boldsymbol{H}$. We can change the direction of the motion of q so that $|\Delta \boldsymbol{F}|$ reaches its maximum value; then, there is $\boldsymbol{H} = \Delta \boldsymbol{F} \times \boldsymbol{v} / (q\mu_0 |\boldsymbol{v}|^2)$.

1.1.3 Maxwell's Equations in Free Space

There are five laws of electromagnetic fields in free space:

$$\oint_C \boldsymbol{E} \cdot d\boldsymbol{s} = -\frac{d}{dt}\int_S \mu_0 \boldsymbol{H} \cdot d\boldsymbol{a} \text{ (Faraday's Law of Electromagnetic Induction)} \tag{1.1a}$$

$$\oint_C \boldsymbol{H} \cdot d\boldsymbol{s} = \int_S \boldsymbol{J} \cdot d\boldsymbol{a} + \frac{d}{dt}\int_S \varepsilon_0 \boldsymbol{E} \cdot d\boldsymbol{a} \text{ (Modified Ampere's Circuital Law)} \tag{1.1b}$$

$$\oint_S \varepsilon_0 \boldsymbol{E} \cdot d\boldsymbol{a} = \int_V \rho dV = Q_{net} \text{ (Gauss's Law)} \tag{1.1c}$$

$$\oint_S \mu_0 \boldsymbol{H} \cdot d\boldsymbol{a} = 0 \text{ (Gauss's Law for Magnetism)} \tag{1.1d}$$

$$\oint_S \boldsymbol{J} \cdot d\boldsymbol{a} = -\frac{d}{dt}\int_V \rho dV = -\frac{dQ_{net}}{dt} \text{ (Law of Charge Conservation)} \tag{1.1e}$$

The first four formulas are often collectively referred to as Maxwell's equations. Since all of the five formulas are line, surface or volume integrals of the field quantities $\boldsymbol{E}$ and $\boldsymbol{H}$ and the source variables ρ and $\boldsymbol{J}$, the formulas are called the integral form of the field laws.

1.1.4 Physical Meaning of Maxwell's Equations

1. Physical meaning of Faraday's law of electromagnetic induction
   In free space, the electromotive force along a closed path is equal to the decreasing rate (the negative of the changing rate with time) of the magnetic flux interlinking with the path (the magnetic flux passing through any one of the curved surfaces bounded by the closed path). In other words, a time-varying magnetic field can generate a vortex electric field.
2. Physical meaning of the modified Ampere's circuital law
   In free space, the ring flow of a magnetic field intensity H along a closed curve (sometimes called magnetomotive force) is equal to the sum of the increasing rate of the cross-linking current and the electric flux. In other words, both the current and the time-varying electric field can generate a vortex magnetic field.
3. Physical meaning of the electric field Gauss's law
   In free space, the electrical flux (electric flux density flux) that passes through a closed curved surface is equal to the amount of net charge in the entire volume

enclosed by the curved surface. In other words, the charge is the source of the electric flux density vector.

4. Physical meaning of Gauss's law for magnetism
   In free space, the net magnetic flux that passes through any closed curved surface is zero; that is, there is no source magnetic charge of the magnetic flux density vector.
5. Physical meaning of the law of charge conservation
   For a system of volume V and external surface S, the net charge in the system changes only when there is charge in or out. If the system has no charge exchange with the outside world, that is, the system is a charge-closed system, then the net charge within the system is constant. In other words, the charge can only be transferred in the form of current, but cannot be generated or disappeared by itself.

1.1.5 The Overall Physical Meaning of Maxwell's Equations

The significance of Maxwell's equations in the electromagnetic field theory is the same as the significance of Newton's laws of mechanics in theoretical mechanics. Any real electromagnetic field behavior obeys Maxwell's equations. In the scope of nonrelativity, the behavior of electromagnetic fields must obey Maxwell's equations in integral form. From the form of the equations, Maxwell's equations describe the relationship between the electromagnetic field quantities $\boldsymbol{E}$ and $\boldsymbol{H}$ and their source quantities ρ, $\boldsymbol{J}$, which is illustrated in Fig. 1.1, where the arrow " →" indicates direct relationship, and "~~ → " indicates a time-varying relationship.

Of all the relationships reflected in Maxwell's equations, there are two situations that need further discussion.

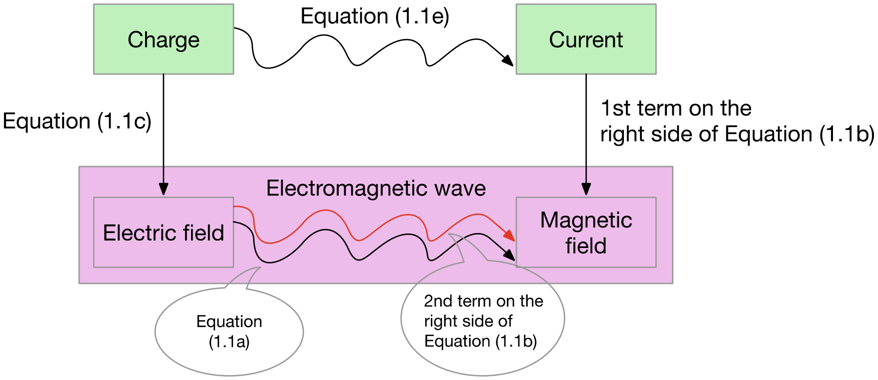


Fig. 1.1 Overall physical meaning of the electromagnetic field law

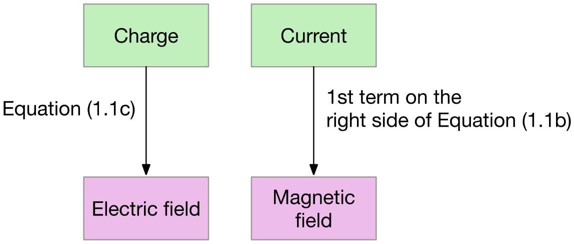


Fig. 1.2 Overall physical meaning of EMF laws when all physical variables are nontime varying

(1) All physical variables are time invariant. At this time, the relationship between the field quantities E and H and their source quantities ρ and J is shown as Fig. 1.2. The electromagnetic field law at this time is:

$$\oint_S \boldsymbol{E} \cdot d\boldsymbol{s} = 0 \tag{1.2a}$$

$$\oint_C \boldsymbol{H} \cdot d\boldsymbol{s} = \int_S \boldsymbol{J} \cdot d\boldsymbol{a} \tag{1.2b}$$

$$\oint_S \varepsilon_0 \boldsymbol{E} \cdot d\boldsymbol{a} = \int_V \rho \, dV \tag{1.2c}$$

$$\oint_S \mu_0 \boldsymbol{H} \cdot d\boldsymbol{a} = 0 \tag{1.2d}$$

$$\oint_S \boldsymbol{J} \cdot d\boldsymbol{a} = 0 \tag{1.2e}$$

…

In this case, there is no mutual coupling between $\boldsymbol{E}$ and $\boldsymbol{H}$. Only two sides of "→" can be retained in Fig. 1.1. This situation is a static (or nontime-varying) electromagnetic field issue.

2. Source quantities are zero, i.e., $\rho = 0$, $J = 0$. In this situation, the expression of the relationship between the electromagnetic field quantities E and H and their source quantities ρ and J is shown in Fig. 1.3. The electromagnetic field law in this situation can be written as

$$\oint_C \boldsymbol{E} \cdot d\boldsymbol{s} = -\frac{d}{dt} \int_S \mu_0 \boldsymbol{H} \cdot d\boldsymbol{a} \tag{1.3a}$$

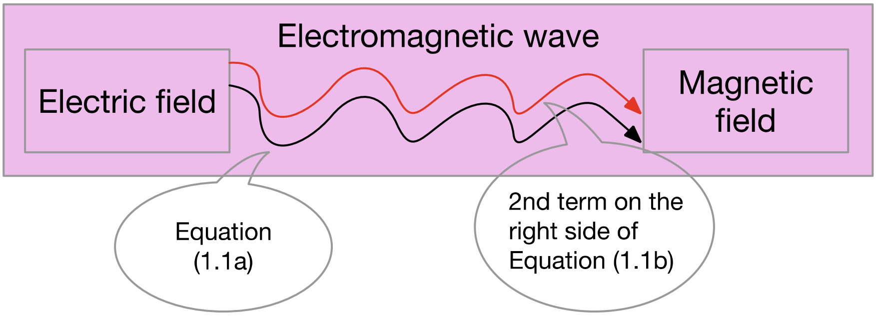


Fig. 1.3 Overall physical meaning of EMF law when the source quantities are zero

$$\oint_C \boldsymbol{H} \cdot d\boldsymbol{s} = \frac{d}{dt}\int_S \varepsilon_0 \boldsymbol{E} \cdot d\boldsymbol{a} \tag{1.3b}$$

$$\oint_S \varepsilon_0 \boldsymbol{E} \cdot d\boldsymbol{a} = 0 \tag{1.3c}$$

$$\oint_S \mu_0 \boldsymbol{H} \bullet d\boldsymbol{a} = 0 \tag{1.3d}$$

From Fig. 1.3, we see that in the region without charge and current, the time-varying electromagnetic field can still exist through mutual coupling, and this form of existence is called the electromagnetic wave. Free space is a typical medium for electromagnetic wave propagation.

Now, we further explain $\oint_C \boldsymbol{H} \cdot \boldsymbol{d}\,\boldsymbol{s} = \frac{\boldsymbol{d}}{\boldsymbol{dt}} \int_S \varepsilon_0 \boldsymbol{E} \cdot \boldsymbol{da}$. After transformation, the formula can be rewritten as $\oint_C \boldsymbol{H} \cdot \boldsymbol{d}\,\boldsymbol{s} = \frac{\mathrm{d}}{\mathrm{d}t} \int_S \varepsilon_0 \boldsymbol{E} \cdot \boldsymbol{d}\,\boldsymbol{a} = \int_S \frac{\partial}{\partial t}(\varepsilon_0 \boldsymbol{E}) \cdot \boldsymbol{d}\,\boldsymbol{a}$. $\frac{\partial}{\partial t}\varepsilon_0 \boldsymbol{E}$ and the current $\boldsymbol{J}$ satisfies the same equation in generating magnetic field in form. $\frac{\partial}{\partial t}(\varepsilon_0 \boldsymbol{E})$ is added to electromagnetic field law by Maxwell for the mathematical integrity. This term is called the displacement current term. After adding this item to Ampere's law and combined with Faraday's law of electromagnetic induction, the existence of electromagnetic waves is theoretically proved. At first, people only thought that this was a mathematical treatment because there was no experimental evidence of the existence of electromagnetic waves. It was not until 1888, nine years after Maxwell's death, that Hertz's electromagnetic experiments proved the genius prophecy of Maxwell.

The purpose of revisiting the overall physical meaning of Maxwell's equations is to provide our reader systematical explanation that the characteristics of the electronic circuits in DC (frequency = 0 Hz) or low frequency (frequency < 100 kHz) and the characteristics of the electronic circuits in RF (frequency > 1 MHz) or microwave (frequency > 1 GHz) are essentially different.

Now, we explain the above with examples.

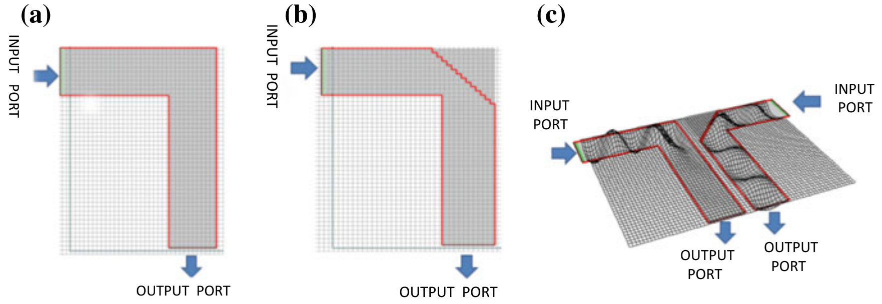


Fig. 1.4 Different transmission characteristics of the microwave transmission line under DC and time-varying conditions

Example 1.1 Connect a metal point to the "ground" with a metal wire; then, the potential of the metal point is the same as the "ground" potential. However, it should be noted that this conclusion can only be strictly established when the entire system is time invariant. In other words, when the frequency is high enough that the linearity (maximum length) of the metal wire can be compared with the wavelength, the phases of the entire metal wire will be unequal since the electrical size (ratio of the geometric size to the wavelength) of the metal wire is large. Therefore, the metal point is no longer equipotential to the "ground" potential.

Example 1.2 Figure 1.4 illustrates a microwave transmission line. The difference between Fig. 1.4a and b is their corners: Fig. 1.4a has a right angle and b has a chamfer angle.

There are input signals at the input port respectively. If the input is a DC signal, there is no difference in the output signal obtained at the output port. However, when the input signal is high frequency or even microwave signal, the situation changes qualitatively. For an easier comparison, the signal transmissions of Fig. 1.4a, b are put together as shown in Fig. 1.4c. It can be seen from this figure that when the corner is a right angle, the output port has no output signal, and a standing wave is formed on the input arm; in case of a chamfer at the corner, there is output signal at the output port.

1.2 Electromagnetic Power Flux

By learning the concept of microwave power flux, our readers can understand that: 1. Even in the case of DC, the energy transmitted by the voltage source to the electronic load can be transmitted through the free space; 2. the properties of devices like capacitors, inductors, and resisters are depend on its energy storage and energy consumption characteristics.

Electromagnetic field is a special form of material existence. Although the electromagnetic field has no static mass, it has the performance of energy and force. For example, solar energy is a kind of electromagnetic energy; the electrostatic force, the magnet's attraction to the ferromagnetic field, and the magnetic force generated around the current indicate that the electromagnetic field has force.

In this section, we will first study the possible transmission channels of electromagnetic energy from the perspective of electromagnetic power influx to further explain the coupling channels in EMC research. Then, the relationship between the properties of the resistors, inductors, capacitors, and their internal electromagnetic fields is studied from the perspective of electromagnetic fields to reveal the nature of the components: Resistors are energy-consuming components, and inductors and capacitors are energy storage components. This research is especially important when a system cannot be described by lumped variables like resistance, inductance, and capacitance.

1.2.1 The Transmission of Electromagnetic Power Flux

In this section, we explain that the electromagnetic fields are capable to carry energy, and wherever there is a field, there is electromagnetic energy.

From the electromagnetic field theory, we see that the electric field energy density for the electrostatic field problem is:

$$w_E = 1/2\varepsilon_0 \boldsymbol{E}(r) \cdot \boldsymbol{E}(r) \quad \left(\boldsymbol{J}/\boldsymbol{m}^3\right) \tag{1.4}$$

The total electric field energy distributed in space is:

$$W_E = \frac{1}{2}\int_V \varepsilon_0 \boldsymbol{E}(r) \cdot \boldsymbol{E}(r) \boldsymbol{d}\, V \quad (\boldsymbol{J}) \tag{1.5}$$

The integration area covers the whole space.

For a constant magnetic field problem, the magnetic field energy density is:

$$w_H(r) = \frac{1}{2}\mu_0 \boldsymbol{H}(r) \cdot \boldsymbol{H}(r)\left(\boldsymbol{J}/\boldsymbol{m}^3\right) \tag{1.6}$$

By integrating the full space, we can get the total magnetic field energy distributed in the whole space

$$W_H = \frac{1}{2}\int_V \boldsymbol{H}(r) \cdot \mu_0 \boldsymbol{H}(r) \boldsymbol{d} V \ (J) \tag{1.7}$$

The definition of $w_E(r)$ and $w_H(r)$ are also applicable to the time-varying field, i.e.,

$$w_E(r,t) = \frac{1}{2}\varepsilon_0 \boldsymbol{E}(r,t)\cdot\boldsymbol{E}(r,t) \quad \left(\boldsymbol{J}/\boldsymbol{m}^3\right) \tag{1.8}$$

$$w_H(r,t) = \frac{1}{2}\mu_0 \boldsymbol{H}(r,t)\cdot\boldsymbol{H}(r,t) \quad \left(\boldsymbol{J}/\boldsymbol{m}^3\right) \tag{1.9}$$

The total energy density of electromagnetic field is

$$w(r,t) = w_E(r,t) + w_H(r,t) \quad \left(\boldsymbol{J}/\boldsymbol{m}^3\right) \tag{1.10}$$

By integrating the full space, we can get the total electromagnetic field energy distributed in the whole space

$$W = \frac{1}{2}\int_{\mathrm{V}} (\varepsilon_0 \boldsymbol{E}(r,t)\cdot\boldsymbol{E}(r,t) + \mu_0 \boldsymbol{H}(r,t)\cdot\boldsymbol{H}(r,t))\boldsymbol{d}\,V \tag{1.11}$$

The analysis above shows that for static electric fields, electric field energy exists wherever $\boldsymbol{E} \neq 0$; for a constant magnetic field, the magnetic field energy exists wherever $\boldsymbol{H} \neq 0$; for electromagnetic waves, as long as the electromagnetic field is not equal to zero, electromagnetic energy exists.

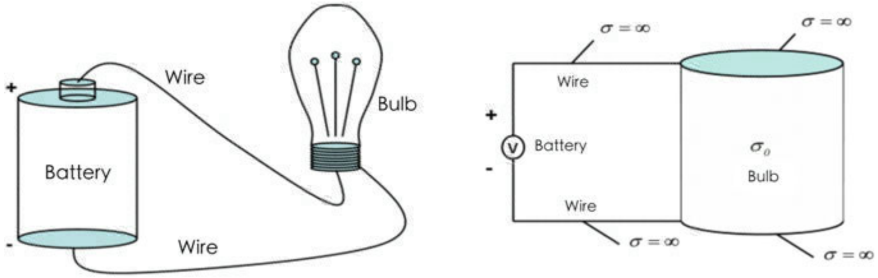
The fact that wherever there is electromagnetic field there is electromagnetic energy indicates that electromagnetic energy can be propagated in space. Here, we use the practical application of the flashlight to explain that even in the case of DC, the energy output from the DC voltage source can be transmitted to the resistor in space between the voltage source and the load. The circuit model of the flashlight is consisted of a DC voltage source, a wire and a resistance. To facilitate an accurate, we modified the model in premise of retaining the working principle.

Now, we take Fig. 1.5 as an example to analyze how the energy supplied from the DC voltage source (battery) is transferred to the load (bulb). Here, we use column coordinate system (the variables are $\boldsymbol{r_c}$, φ and z, and the unit vectors are $\hat{i}_{r_c}$, $\hat{i}_\varphi$ and $\hat{i}_z$). Then, we build a analysis model as shown in Fig. 1.5c. There is a linear, uniform, cylindrical resistor rod (with electric conductivity σ,length d, and radius a). Its two ends are connected to two circular parallel plates with conductivity σ equals ∞,and radius $b > a$. At the position of $r_C = b$, the system is excited by a circularly symmetric voltage source and the potential difference between the plates is kept to be a constant V_0.

This is a system unrelated to φ. The electric field between the plates is a uniform field, i.e.,

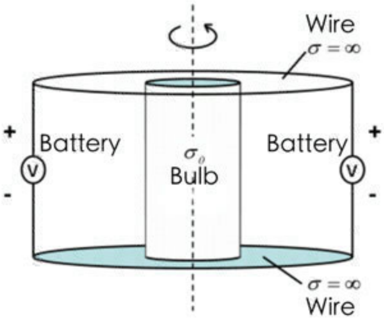
$$\mathbf{E} = -\mathbf{i}_z \frac{V_0}{d} \quad (\mathrm{V/m}) \tag{1.12}$$

Under the excitation of an electric field, a current is generated in the resistance bar, and the current density is



(a) Flashlight;

(b) working principle of a flashlight;



(c) analysis model.

Fig. 1.5 Example of power flux analysis

$$\mathbf{J}(r) = \sigma \mathbf{E}(r) = -\mathbf{i}_z V_0 \sigma / d \quad (A/m^2)$$

The total current in the rod is $I_0 = \int_S \mathbf{J}(r) \cdot \mathrm{d}\mathbf{a} = \sigma V_0 \pi a^2 / d \quad (A)$.

Using Ampere's loop law, the magnetic field of the system can be determined as:

$$\boldsymbol{H} = \begin{cases} -\boldsymbol{i}_\varphi \frac{I_0 r_C}{2\pi a^2} & (0 \le r_C < a, 0 < z < d) \\ -\boldsymbol{i}_\varphi \frac{I_0}{2\pi r_C} & (a < r_C < b, 0 < z < d) \ (\boldsymbol{A/m}) \\ 0 & (r_C > b, 0 < z < d) \end{cases} \tag{1.13}$$

Poynting vector is $\mathbf{S}(r) = \mathbf{E}(r) \times \mathbf{H}(r)$. It is not difficult to see that in the area of $0 \le r_C < a$, there is

$$\mathbf{S}(r) = \mathbf{E}(r) \times \mathbf{H}(r) = \left(-\mathbf{i}_z \frac{V_0}{d}\right) \times \left(-\mathbf{i}_\varphi \frac{I_0 r_C}{2\pi a^2}\right) = -\mathbf{i}_{r_C} \frac{V_0 I_0 r_C}{2\pi d a^2} \quad \left(\mathrm{W/m^2}\right) \tag{1.14}$$

In the area of $a < r_C < b$, there is