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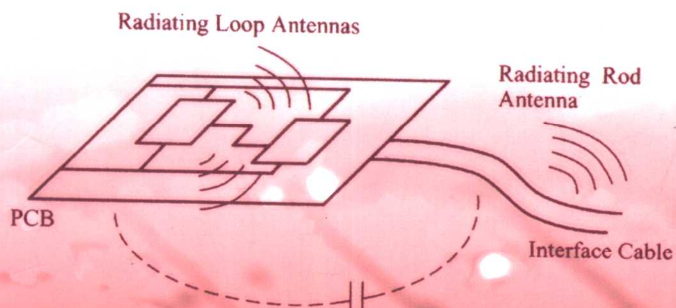
电磁兼容基础与应用（英文版）

Fundamental of Electromagnetic Compatibility and Application

赵阳　主　编

SEE Kye Yak　副主编



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Fundamental of Electromagnetic Compatibility and Application

主　编　赵　阳（ZHAO Yang）
副主编　See Kye Yak
参　编　李世锦（LI Shijin）

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随着电气与电子技术的飞跃发展，产品的电磁兼容（EMC）性正受到越来越多的电子、电气工程师和广大工程技术人员的关注和重视。本书是由中外作者合作编写的英文版教材。全书共6章，分基础、传导和辐射三大部分，内容包括：电磁兼容导论、电磁兼容的基础知识、传导性电磁干扰噪声分析与抑制、辐射性电磁干扰噪声分析与抑制、传导性电磁干扰噪声诊断与抑制策略以及辐射性电磁干扰噪声诊断与抑制策略。本书对电磁兼容相关技术进行了精选，并融入了一些最新发展动向和作者的部分研究成果。全书结构科学合理，层次分明，适于教学。此外，本书从实际工作需要出发，结合了电类专业的特点，图文并茂，覆盖面广，内容由浅入深，具有较强的实用性和可选性。

本书可作为电气与电子类专业的本科生以及研究生的双语教学教材，也可作为电子与电气工程师进行 EMC 培训和学习的教材或参考资料。此外，本书也可供 EMC 测试工程师和工程管理人员参考。

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前　言

随着电气与电子技术的飞跃发展，产品的电磁兼容（EMC）性正受到越来越多的电子、电气工程师和广大工程技术人员的关注和重视。为了满足符合性测试的要求和保障设备的稳定性与可靠性，设计人员需要对系统进行完备的 EMC 设计。

电磁兼容学科是一门综合性交叉学科，与很多学科相互渗透、结合，是自然科学和工程学的一个交叉学科，其理论基础宽广，工程实践综合性强，也是电力、电子和其他相关从业工程师必须掌握的基础知识和技术。

我国的电磁兼容性研究与国际上科学技术发达的国家相比，起步较晚，差距较大。加入 WTO 后，国产用电设备和电气、电子产品要站稳国内市场和进入国际市场，就必须通过和符合产品的电磁兼容性强制检测和检验标准，因此有必要对在校大学生和广大的电气与电子工程技术人员进行电磁兼容性的理论和技术教育。但长期以来，国内在 EMC 方面的技术参考资料还不全面，对于在校大学生和广大设计人员来说，有特色、系统性强、理论与工程实际紧密结合的 EMC 教材和参考资料尚不多见。本书正是基于这一目的而编写的，主要作为电气与电子类专业的本科学生以及研究生双语教学用书，也可以作为电气、电子工程师进行 EMC 培训和学习的教材或参考资料。

本书分电磁兼容基础、传导和辐射三大部分，首先从电磁兼容的基本概念入手，介绍了电磁兼容分析的基本方法和传导、辐射性电磁干扰噪声的分析与抑制；接着介绍了传导、辐射性电磁干扰噪声诊断与控制策略；最后介绍了电磁兼容的有关实验。

本书从实际工作需要出发，结合了电类专业的特点，覆盖面广，内容由浅入深，具有较强的实用性和可选性。本书图文并茂，浅显易懂，旨在让初学者对电磁兼容有一个总体认识，同时也适用于有关专业技术人员。书中提出的方法简单易行，是作者多年来实践得出的结果，适宜于工程应用。

本书主要由南京师范大学电磁兼容研究室赵阳博士与新加坡南洋理工大学电气与电子工程学院（Nanyang Technological University，EEE School）电磁兼容实验室 See Kye Yak 博士合作完成。两位教授多年来一直从事电磁兼容的教学和研究工作，并已取得许多成果。

本书由赵阳任主编，编写了第 1、3、5 章，并负责全书的整理和统稿工作；See Kye Yak 任副主编，编写了第 4、6 章；李世锦编写了第 2 章。在本书编写过程中，沈雪梅、尹海平做了大量的文字输入和校对工作，在此表示感谢。

在本书完稿之际，对书中所列参考文献的作者一并表示感谢；同时感谢南京师范大学教材出版基金的资助。

由于时间仓促，水平有限，书中难免有不当或错误之处，敬请广大读者批评指正。

编　者

Preface

Due to worldwide trends of imposing electromagnetic compatibility (EMC) regulations on electronic and information technology products, EMC education has been gaining more attention than before in the universities. Without some EMC training, the undergraduates, who will become the future electronic engineers, when they graduate and enter the industry, will have to learn the EMC design techniques through the painful trial-and-error process. The companies that hire these engineers also suffered from higher design cost and unnecessary production delay, which are crucial surviving factors in today's competitive markets.

Therefore, basic understanding of electromagnetic interference (EMI) generation mechanism and the EMI mitigation techniques will help to avoid last minute surprises as far as possible at the product design stage. This is a rational and economical approach when compared to leaving the EMI problems to be tackled and mitigated after the product is developed and assembled.

The growing importance of EMC education motivates the two authors from two countries (China and Singapore) to write this textbook. Since there are already many EMC texts and references available in market, the text book has to be different to avoid duplication of those wonderful textbooks published by other EMC experts. As the scope of EMC is rather wide, it is impossible to cover all EMC topics in one book, and the authors decided to focus on two main topics, the conducted EMI and the radiated EMI. The book begins with the fundamental theory with little complicated mathematics so that the undergraduates could easily understand the fundamentals without being scared by the electromagnetic theory.

The best part of the book is the practical examples and case studies, which constitutes around 50% of the content. The authors strongly believe that these practical examples and case studies allow the students to appreciate the importance of EMC design at the initial design stage. At the end of this course, the students will be equipped with the necessary fundamentals in EMC design so that they could apply what they have learnt without fear and panic when they design products for the international market.

The first author (Dr. ZHAO Yang) wrote Chapters 1, 3 and 5, covering introduction of EMC and conducted EMI issue. The second author (Dr. SEE Kye Yak) contributed Chapters 4 and 6, with emphasis on radiated EMI issue. The third author (Mr. LI Shijin) wrote Chapter 2 of background knowledge of EMC. All the authors sincerely hope that the joint effort from the authors would help you to be a better design engineer. Since this is the first edition, errors and mistakes are sometimes unavoidable even the authors have put in their best editing and checking effort. Any feedbacks and comments from the readers will be welcomed and appreciated. Hopefully, the next edition could improve further to benefit more readers.

ZHAO Yang, China
SEE Kye Yak, Singapore
LI Shijin, China

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We wish to express our sincere gratitude to our universities, Nanjing Normal University (NNU) of China and Nanyang Technological University (NTU) of Singapore, for their support and encouragement throughout the writing of this book.

We would particularly like to acknowledge the assistance extended by our many colleagues in NNU and NTU in the forms of stimulating discussions and giving comments. We also would like to thank our research students for their permission to include some of the measurement results in this book.

We are indebted to our wives, Xiaohui (Dr. Zhao's wife) and Lydia (Dr. See's wife). Their support and patience made our writing a more pleasant task. We also would like to thank our children, Bonan, Truman, Gabrielle and Zachary for their understanding when we are busy preparing the manuscript. They brought us much happiness during the process of writing the book, which makes our task a wonderful experience.

The funding support from Nanjing Normal University for publishing this book is greatly appreciated.

Special thanks are also given to two postgraduates, Shen Xuemei and Yin Haipin, for their careful work in drawing the figures and checking the content.

Finally, we would like to acknowledge all those authors of reference materials listed in this book.

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Contents

Chapter 1 Introduction to Electromagnetic Compatibility

1.1 Basic Concepts of EMC

1.1.1 Introduction

In the past decade, the wide spread use of high-speed digital-operated electronic devices has resulted in wide-spectrum unwanted electromagnetic emissions. On the other hand, the exponential growth in wireless communications has pushed the government telecommunication agencies to release more frequency spectrum for new wireless applications, such as Bluetooth, GSM Mobile, WLAN, UWB, etc. Hence, without proper regulatory control on the amount of electromagnetic emissions from the electronic devices, these wireless communications will be interrupted by the so called Electromagnetic Interference (EMI). Modern electronic devices must therefore be able to function properly in an increasingly crowded electromagnetic environment and at the same time, they should not cause interference to other communication users. Thus, the minimization of electromagnetic interference and susceptibility has become one of the major electronic product design issues. Often the effects of EMI are not discovered until product testing occurs. The resolution of interference problems in the late phases of product development often involves additional components which add to system's cost and complexity. With the world-wide trend in imposing EMI regulatory control, all electronic products must meet the applicable EMI specifications in the EMI-regulated countries, such as USA, European Community, Japan, Korea, etc. It is therefore desirable that electromagnetic interference issues, and compliance with federal regulations regarding emissions and susceptibility, be addressed in the initial stages of product design. As a result, much interest has recently centered on the area of electrical engineering that has come to be known as Electromagnetic Compatibility (EMC).

Many engineers have misconceptions on the roots of EMC-related problems and therefore have faced great difficulty to resolve these problems. Much of the material presented to electrical engineering students represents specializations of broader principles. The most fundamental understanding of the behavior of electronic devices and systems requires application of Maxwell's equations and signal analysis techniques. However, such application to simple devices and circuits is often cumbersome. To avoid this complexity, an approximate analysis technique, usually referred to as electric circuit theory, is used to describe the behavior of devices operated at low frequency. For example, Kirchoff's Voltage Law and Kirchoff's Current Law arise from Faraday's Law and Ampere's Law, respectively. Unfortunately, the basic concepts of circuit theory and electromagnetic (as well as other areas of electrical engineering such as signal processing and control theory) are often presented as being completely detached from one another. For this reason, most engineers (mistakenly) expect that the familiar basic circuit elements, such as resistors, inductors and capacitors, always behave in the ideal, low frequency manner described by the circuit theory presented in undergraduate coursework.

EMC involves the operation of these and other familiar devices in a regime where the special cases and simplifications that are associated with "normal behavior" break down, and requires one to return to a more fundamental set of rules to describe the behavior of these devices. It should be remembered that effects described by fundamental electromagnetic principles are always present, and are simply more pronounced under certain conditions. "Non-ideal behavior" is, in fact, a misnomer, because it implies that devices are functioning in an abnormal way, when they are really behaving in a perfectly natural way. It is only through the application of fundamental principles that the behavior of devices under all operating conditions is predictable. What makes the task of producing electromagnetically compatible systems particularly difficult is that, in addition to understanding the broader principles which govern device behavior, the designer often cannot anticipate what types of interference devices will encounter, and must prepare for all contingencies. For instance, it is impossible to know where certain ubiquitous electronic devices such as notebook computers will be operated. Notebooks are commonly used in the home, in automobiles, at construction sites, onboard airplanes, and even aboard manned spacecraft in Earth orbit. Each of these environments presents unique hazards and also requires a variety of emission limits. The same notebook computer which must be designed to function in the presence of a hair dryer also cannot interfere with the instrument landing system of a commercial airliner. In addition, particularly in vehicles such as automobiles and airplanes, devices whose design has changed little in decades may be placed close to state-of-the-art solid state devices. For these reasons, systems must be designed not only to minimize emissions, but also to be immune from external interference. Unfortunately, as the electromagnetic environment becomes more complex, this goal becomes more difficult to achieve.

1.1.2 EMC Terms

Some common technical terms and abbreviations in the EMC community will be described below for the benefits of some readers who are new to this area.

Electromagnetic Compatibility (EMC)

The capability of electrical and electronic systems, equipment, and devices to operate in their intended electromagnetic environment within a defined margin of safety, and at design levels or performance, without suffering or causing unacceptable degradation as a result of electromagnetic interference. (Extracted from ANSI C64.14-1992)

Electromagnetic Interference (EMI)

The lack of EMC, since the essence of interference is the lack of compatibility. EMI is the process by which disruptive electromagnetic energy is transmitted from one electronic device to another via radiated or conducted paths (or both). In common usage, the term refers particularly to

RF signals, but EMI can occur in the frequency range from "DC to daylight".

Radio Frequency (RF)

A frequency range containing coherent electromagnetic radiation of energy useful for communication purposes-roughly the range from 10 kHz to 100 GHz. This energy may be transmitted as a by-product of an electronic device's operation. RF is transmitted through two basic modes.

Radiated Emissions

The component of RF energy that is transmitted through a medium as an electromagnetic field. Although RF energy is usually transmitted through free space, other modes of field transmission may occur.

Conducted Emissions

The component of RF energy that is transmitted through a medium as a propagating wave, generally through a wire or interconnecting cables. LCI (Line Conducted Interference) refers to RF energy in a power cord or AC mains input cable. Conducted signals do not propagate as fields but may propagate as conducted waves.

Susceptibility

A relative measure of a device or a system's propensity to be disrupted or damaged by EMI exposure to an incident field of signal. It is the lack of immunity.

Immunity

A relative measure of a device or system's ability to withstand EMI exposure while maintaining satisfactory functional performance.

Electrostatic Discharge (ESD)

A transfer of electric charge between bodies of different electrostatic potential in proximity or through direct contact. This definition is observed as a high-voltage pulse that may cause damage or loss of functionality to susceptible devices.

Radiated Immunity

A product's relative ability to withstand electromagnetic energy that arrives via free-space propagation.

Conducted Immunity

A product's relative ability to withstand electromagnetic energy that penetrates it through external cables, power cords, and I/O interconnects.

Suppression

The process of reducing or eliminating RF energy that exists without relying on a secondary method, such as a metal housing or chassis. Suppression may include shielding and filtering as well.

1.1.3 Effects of EMI

The effects of EMI are extremely variable in character and magnitude ranging from simple annoyance to catastrophe. Some examples of the potential effects of EMI are:

- Interference to television and radio reception

- Loss of data in digital systems or in transmission of data
- Delays in production of equipment exhibiting intra-unit, subsystem or system level EMI
- Malfunction of medical electronic equipment (e.g. neonatal monitor, heart pacemaker)
- Malfunction of automotive microprocessor control systems (e.g. braking or truck anti-jackknife systems)
- Navigation equipment malfunction
- Inadvertent detonation of explosive devices
- Malfunction of critical process control functions (e.g. oil or chemical industry)

To correct EMI problems occurring after equipment is designed and in production is usually expensive and results in program delays which may adversely affect the acceptance of a new product. It is preferable to follow good EMC engineering practice during the equipment design and development phases. Our goal should be to produce equipment capable of functioning, in the predicted or specified electromagnetic environment and which does not interfere with other equipment or unduly pollute the environment. That is, to achieve EMC. The techniques of EMC prediction described in subsequent chapters will aid in meeting the goal of EMC when applied at the design stage. These same techniques of analysis and modeling are applicable to EMI control and problem solving or in the location of out of specification emissions. It is in the area of emission reduction where analysis is most likely to be supplemented by measurement and diagnostic intervention. However, the value of simple EMI measurements made as early as feasible in the design, breadboard and prototype phases can not be emphasized enough.

1.1.4 Typical Noise Path

A block diagram of an EMI situation is shown in Fig. 1-1. Three elements are necessary to produce an EMI problem. There must be an interference source, a receptor circuit that is susceptible to the interference source and a coupling channel to transmit the unwanted signal from the source to the receptor. The first step in analyzing and solving an EMI problem is to identify the EMI source, the receptor is and how the source and receptor are coupled. There are three possible techniques to solve the problem: (1) to suppress the EMI source, (2) to improve the EMI immunity of the receptor, or (3) to break the coupling channel. In some cases, EMI problems are resolved by applying two or all three techniques.

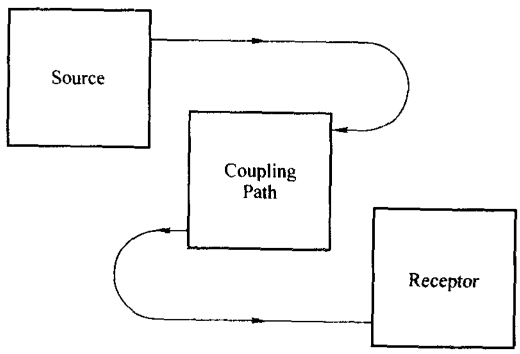

Fig. 1-1 A simple electromagnetic interference (EMI) coupling model

Using Fig. 1-2 as an example, it shows a shielded dc motor connected to its motor control circuit. The noise generated by the motor is interfering with a low-signal circuit in close proximity. The noise from the motor is conducted out of the shield on the leads going to the drive circuit. The noise also radiated from the leads and coupled to the low-signal circuitry. In this example, the EMI source is caused by the interruption of current between the carbon brushes and the commutator of the motor. There are two coupling paths: conduction on the motor leads and radiation from the leads. The receptor is the low-signal circuit. In this case, the noise can be suppressed by adding capacitor across the brushes, inserting a filter between the motor and the control circuit, or using shielded leads. If necessary, all the three techniques must be employed solve the EMI problem.

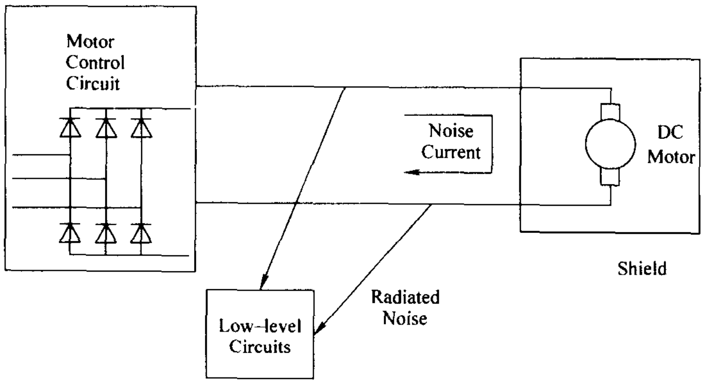

Fig. 1-2 An example of a shielded DC motor with motor-drive circuit

1.1.5 Benefits of good EMC Design

There are many benefits for good EMC design. Besides maintaining a good product reputation, four benefits in particular are worth mentioned:

1. Safety

In any product design, safety is the most important issue. The number of reported injury cases that linked to malfunction of electronic product caused by EMI has been increasing. As more consumers own portable electronic devices such as cellular phones and notebook computers, the potential for possible safety hazards due to EMI is expected to increase, if these devices are not EMC compliant. Also as more electronic instruments are incorporated in complex vehicle systems, as in automobiles and airplanes, the possibility of EMI induced malfunctions may occur more frequently. Several examples of EMC related problems that resulted in injury are included at the end of this chapter.

2. Reduction of Product Design Cost

It is generally far less expensive to identify and fix problems during the design phase of a product, rather than during the production phase. Often, once a problem is identified during the production phase, the product must reenter the design phase to properly correct the problem.

3. Increased Reliability

Proper EMC techniques applied during the design phase can increase product reliability. Late development fixes often require the addition of extra components which not only increase cost, but compound system complexity. This added complexity tends to decrease the reliability of the product.

The added components may also adversely affect the functionality and operation of the product. For example, the incorporation of shielding in an automobile may increase weight, thus reducing performance, and limiting fuel efficiency. In addition, product manufacturing may become more difficult and require longer time for assembly line personnel to perform additional tasks.

4. Legality

As EMI problem may lead to a safety issue, electronic devices must therefore meet various legal requirements in nearly every country in the world. Devices which do not meet these requirements cannot legally be sold, or in most cases used. Improperly EMC designed devices failing to meet these legal requirements may cause damage to other equipment and injury to personnel, which can lead to costly lawsuits.

1.2 EMC Standards and Measurements

1.2.1 EMC Standards

The need for regulations stems from either complaints regarding EMI to electronic products used in both residential and commercial applications or from the requirement to protect allocated communication services. The regulations control not only emissions but also susceptibility (or immunity) of an electronic device. Europeans have taken the lead in mandating immunity tests; in North America, however, these same tests are only voluntary at the time of this writing. Not all countries have the same EMC requirements. In fact, each country is responsible to enforce its own requirements. This does not, however, mean that each country has a unique set of EMC requirements. In fact, for harmonization purposes, the various EMC requirements set forth by all the countries of the world are rather similar, and many countries, except North America, are moving toward accepting international EMC standards issued by CISPR (it is a French abbreviation, the English translation means International Special Committee on Radio Interference). The EMC standards issued by CISPR cover a wide range of electronic products. For example, for product falls under the category of Information Technology Equipment (ITE), the specific EMC standard is CISPR 22. These standards are always revised regularly by the sub-committee under CISPR.

In the United States the Federal Communications Commission (FCC) is charged with the regulation of radio and wire communication. Radio frequency devices are the primary concern in EMC. A radio frequency device is defined by the FCC as any device that is capable of emitting radio frequency energy by radiation, conduction or other means whether intentionally or not. Radio frequencies are defined by the FCC to be the range of frequencies extending from 9 kHz to 300 GHz. Some examples of radio frequency devices are digital computers whose clock signals generate radiated emissions, blenders that have dc motors where arcing at the brushes generates energy in this frequency range, and televisions that employ digital circuitry. In fact nearly all digital devices are considered radio frequency devices. With the advent of computers and other digital devices, the FCC realized that it was necessary to impose limits on the electromagnetic emissions of these devices in order to minimize their interference potential to other radio and wire communications. As a result the FCC set limits on the radiated and conducted emissions of digital devices. Digital devices are defined by the FCC as any unintentional radiator (device or system) that generates and uses timing pulses at a rate in excess of 9000 pulses (cycles) per second and uses digital techniques. All electronic devices with digital circuitry and a clock signal in excess of 9 kHz are covered under this rule, although there are a few exceptions.

The law makes it illegal to market digital devices that have not had their conducted and radiated emissions measured and verified to be within the limits set for by the FCC regulations. This means that digital devices that have not been measured to pass the requirements can not be sold, marketed, shipped, or even be offered for sale. Although the penalties for violating these regulations include fines and or jail time, companies are more concerned with the negative publicity that would ensue once it became known that they had marketed a product that fails to meet FCC regulations. Furthermore, if the products in question were already made available to the public, the company would be forced to recall the products. Thus it is important that every unit that a company produces is FCC compliant. Although the FCC does not test each and every module, they do perform random tests on products and if a single unit fails to comply, the entire product line can be recalled.

The FCC has different sets of regulations for different types of digital devices. Devices that are marketed for use in commercial, industrial or business environments are classified as Class A digital devices. Devices that are marketed for use in residential environments are classified as Class B digital devices. In general the regulations for Class B devices are more stringent than those for Class A devices. This is because in general digital devices are in closer proximity in residential environments, and the owners of the devices are less likely to have the abilities and or resources to correct potential EMI problems. Fig. 1-3 shows a comparison of the Class A and Class B conducted emissions limits, where you can clearly see that the regulation for Class B devices is stricter than those for Class A devices. Personal computers are a subcategory of Class B devices and are regulated more strictly than other digital devices. Computer manufacturers must test their devices and submit their test results to the FCC. No other digital devices require that test data be sent to the FCC, rather the manufacturer is expected to test their own devices to be sure they are electromagnetically compatible and the FCC will police the industry through testing of random product samples.

Since the FCC regulations are concerned with radiated and conducted emissions of digital products, it is useful to understand what these emissions are. Conducted emissions are the currents that are passed out through the unit's AC power cord and placed on the common power net. Conducted emissions are undesirable because once these currents are onto the building wiring they radiate very efficiently as the network of wires acts like a large antenna. The frequency range of conducted emissions extends from 450 kHz to 30 MHz. Devices are tested for compliance with conducted emissions regulations by inserting a line impedance stabilization network (LISN) into the unit's AC power cord. Current passes through the AC power line and into the LISN, which measures the interference current and outputs a voltage for measurement purposes. The actual FCC regulations set limits on these output voltages from the LISN even though the current is truly being regulated. Radiated emis-

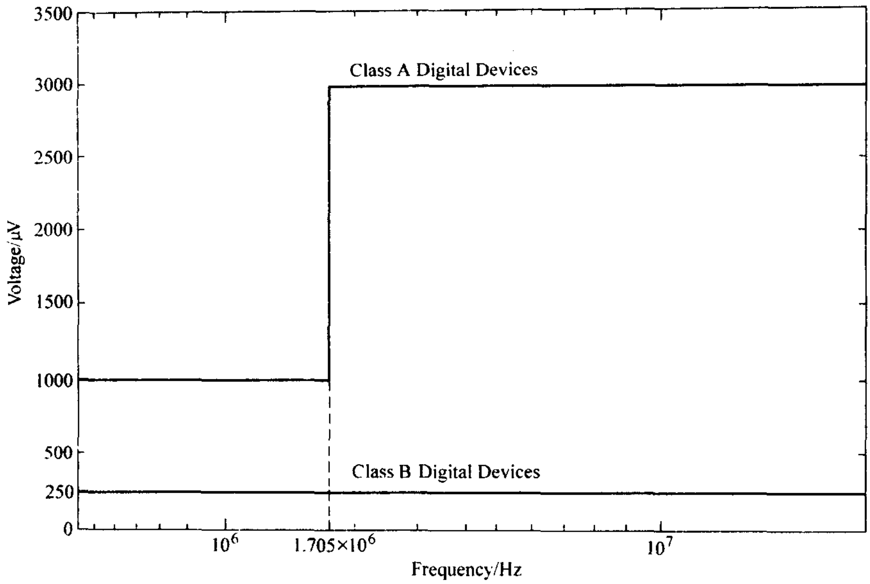

Fig. 1-3 FCC conducted emission limits

sions are the electromagnetic fields radiated by the device that may be received by other devices, and cause interference in those devices. Although radiated emissions have both electric and magnetic field components, the FCC and other regulatory agencies only require that electric fields be measured for certification. The magnitudes of these fields are measured in dB $\mu V/m$ and the frequency range for radiated emissions extends from 30 MHz to 40 GHz. Radiated field measurements for FCC compliance are done in either a semi-anechoic chamber or at an open field test site. The product under test must be rotated so that the maximum radiation will be achieved and measurements must be made with the measurement antenna in both vertical and horizontal polarizations with respect to the ground plane.

The method for measuring radiated emissions varies depending on the type of device being measured. Class A digital devices must be measured at a distance of 10 m from the product and Class B devices are to be measured at a distance of 3 m from the product. As explained earlier, the Class B devices, which are marketed for residential use, have stricter regulations and thus must be measured in closer proximity than Class A devices. Fig. 1-4 displays the radiated emission limits that are defined by the FCC for Class A and Class B digital devices. Because the measurement distances defined by the two requirements are different, we must scale the measurement distances so that they are both at the same distances in order to achieve an accurate comparison. One way to do this is with the inverse distance method, which assumes that emissions fall off linearly with increasing distance to the measurement antenna. Thus emissions at 3 m are assumed to be reduced by 3/10 if the antenna is moved out to a distance of 10 m. So, to translate Class A limits from a distance of 10 m to 3 m, we add $20\log10\ (3/10) = 10.46$ dB to the Class A limits. This approximation is only valid, however, if the measurements are taken in the far field of the emitter. We can assume that the far