ANALYTICAL AND EXPERIMENTAL STUDY OF THE ELECTRIC SHIELDING EFFECTIVENESS OF A METALLIC ENCLOSURE FOR OFF-CENTRED APERTURES

FARHANA BINTI AHMAD PO'AD

A thesis submitted in fulfillment of the requirements for the award of Master of Electrical Engineering

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

MARCH 2007

This thesis is especially dedicated to my beloved father Ahmad Po'ad Bin Haji Mohd. Said, mother Rokiah Binti Hashim, husband Jusrorizal Fadly Bin Jusoh, Nabilah and Anas Akmal

ACKNOWLEDGEMENT

Many people have contributed directly or indirectly to the completion of this thesis and their assistance is gratefully acknowledged. First of all, I would like to express my gratitude to my supervisor, Prof. Dr. Mohd. Zarar Bin Mohd. Jenu for giving me the opportunity to work on this research work. His willingness to teach attitude and unfailing patient has been a great motivation for me to excel in my work. Without his guidance and invaluable time spent with me in this research work, this thesis would not have been completed successfully.

I would also like to express my heartiest thankful to EMC Center staff Mr. Mohd. Erdi Bin Ayob and Mr. Mohd. Nazeri Bin Sarmijan who helps me a lot in completed my laboratory and experimental work.

My gratitude also goes out to my father Ahmad Po'ad Bin Mohd. Said and my mother Rokiah Binti Hashim for their moral support and blessing since the beginning. Special dedicated thanks to my husband Jusrorizal Fadly Bin Jusoh for being always there and gave me a lot of moral support as well as encouragement and accompanies me going through all the ups and downs. My appreciation and thanks to my friends as well for their constructive idea, comment and critics throughout the preparation of my research work.

Last but not least, I would like to thank GOD for giving me this wonderful privilege to work on my research work and entire lesson I've learned along the way. Surely it is an experience which will prove invaluable later in life. Needless to say, without all the above help and support, the writing and production of this thesis would not have been possible. Thank you.

ABSTRACT

An electromagnetic shielding is frequently used to protect against external fields and leakage from electronic products to meet the electromagnetic compatibility (EMC) requirement. However, it is a great challenge to design a practical electromagnetic shield because its integrity is often compromised by apertures and slots used to accommodate ventilation or access to interior components. Such openings allow exterior fields to be coupled onto printed circuit boards (PCBs), thus inducing current and voltage on interior conductors. This phenomenon will degrade the shielding effectiveness (SE) of the enclosure. This research is performed to investigate the effects of apertures on the SE of a rectangular metallic enclosure for off-centred apertures by using an analytical formulation and experimental study. The theories developed by other researchers have been extended to take into account the contribution of higher order modes and off-centred apertures in the enclosure. The electric shielding effectiveness, S_E were calculated as a function of frequency, enclosure dimensions, aperture dimensions, aperture locations and various observation points by employing a transmission line equivalent circuit approach. The extended formulation applies only to rectangular enclosures with rectangular apertures, but simple modifications were included to account for square, circular, multiple apertures and the effect of the enclosure contents. Generally, the analytical results of the S_E are in good agreement with measurement results which were conducted in a Gigahertz Transverse Electromagnetic (GTEM) cell in the range of frequency from 10 MHz to 1 GHz. As an example, the S_E at 600 MHz using analytical formulation has 92% similarity compared to measurement results. It was also found out that by taking into account five modes above the TE_{10} will contribute an additional 35 dB to the S_E at 800 MHz. This indicates the significance of multimode in determining S_E for enclosure with off-centred aperture. In addition, the results agree with present understanding on the dependence of S_E on aperture sizes, aperture shapes, aperture locations and effect of electromagnetic losses in the enclosure. The reduction of S_E by about 9.5 dB due to multiple apertures indicated by 20 log n where n is the number of apertures was also successfully endorsed in this work. The findings generated from this research work can be used as design rules by designers of practical shielded enclosures. Future works can be carried out to incorporate enclosures of various shapes and sizes at frequencies greater than 1 GHz.

ABSTRAK

Pelindung elektromagnet digunakan untuk melindungi produk-produk elektronik daripada medan luaran bagi memenuhi keperluan keserasian elektromagnet (EMC). Ia merupakan cabaran yang hebat untuk merekabentuk sebuah pelindung elektromagnet yang praktikal disebabkan oleh ketelusannya seringkali dikompromi oleh bukaan dan lubang-lubang kecil yang digunakan bagi menampung pengudaraan dan laluan masuk kepada komponen-komponen dalaman. Sesetengah bukaan membenarkan medan-medan luaran untuk berganding di atas papan litar bercetak (PCBs), seterusnya menghasilkan arus dan voltan pada konduktor dalaman. Fenomena ini akan merendahkan keberkesanan pelindung (SE) bagi sesebuah penutup logam. Kajian ini dilaksanakan bagi mengenalpasti kesan-kesan bukaan terhadap SE dengan menggunakan perumusan analitikal dan kaedah eksperimental. Teori yang telah dibangunkan oleh pengkaji-pengkaji terdahulu telah dilanjutkan dengan mengambil kira mod-mod berkedudukan tinggi (*higher order modes*) dan bukaan pelbagai kedudukan pada penutup logam. SE bagi medan elektrik, S_E diukur sebagai fungsi kepada frekuensi, dimensi penutup logam dan bukaan serta kedudukan bukaan dan titik pemerhatian pada penutup logam dengan menggunakan pendekatan litar setara bagi talian penghantaran. Perumusan ini hanya benar digunakan bagi penutup logam yang berbentuk segiempat tepat dengan bukaan berbentuk segiempat tepat, segiempat sama, bulatan, bukaan berganda dan mengambil kira kesan terhadap kandungan penutup logam. Keseluruhannya, perumusan analitikal mempunyai hubungan baik dengan eksperimental yang dijalankan di dalam Gigahertz Transverse Electromagnetic (GTEM) cell dari frekuensi 10 MHz hingga 1 GHz. Sebagai contoh, S_E pada frekuensi 600 MHz bagi kaedah analitikal menunjukkan 92 % persamaan dibandingkan dengan keputusan eksperimental. Dapatan mendapati dengan mengambil kira lima mod di atas TE_{10} akan menyumbang kepada pertambahan S_E sebanyak 35 dB pada frekuensi 800 MHz. Ini menunjukkan kepentingan pelbagai mod dalam menentukan S_E untuk bukaan pelbagai kedudukan. Dapatan bersetuju dengan kajian terdahulu mengenai kebergantungan S_E terhadap saiz bukaan, bentuk bukaan, kedudukan bukaan dan kesan terhadap kehilangan elektromagnet di dalam penutup logam. Penurunan S_E sebanyak 9.5 dB disebabkan oleh bukaan berganda dinyatakan oleh 20 log n di mana n ialah bilangan bukaan telah dibuktikan di dalam kajian ini. Dapatan kajian ini boleh digunakan sebagai panduan merekabentuk pelindung penutup yang praktikal oleh perekabentuk. Kajian lanjutan boleh dijalankan bagi penutup logam yang terdiri dari pelbagai bentuk dan saiz pada frekuensi melebihi 1 GHz.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FIGURE	TITLE	PAGE

LIST OF SYMBOLS/ ABBREVIATIONS

E	-	Electric Field Intensity *(V/m)*
H	-	Magnetic Field Intensity *(A/m)*
f	-	Frequency *(Hz)*
α	-	Attenuation Constant *(Np/m)*
β	-	Phase Constant *(rad/m)*
γ	-	Propagation Constant *(m^{-1})*
δ	-	Skin Depth *(m)*
ε	-	Relative Permittivity *(F/m)*
ε_0	-	Relative Permittivity of Free-Space ($\varepsilon_0 = 8.854 \times 10^{-12} F/m$)
ε_r	-	Relative Permittivity of Material (dimensionless)
μ	-	Relative Permeability *(H/m)*
μ_0	-	Relative Permeability of Free-Space ($\mu_0 = 4\pi \times 10^{-7} H/m$)
μ_r	-	Relative Permeability of Material (dimensionless)
σ	-	Conductivity of Material *(S/m)*
σ_r	-	Relative Conductivity (dimensionless)
η	-	Intrinsic Impedance (Ω)
η_0	-	Impedance of Free-Space ($\eta_0 = 377\Omega$)
λ	-	Wavelength *(m)*
v	-	Velocity *(m/s)*
ω	-	Angle Frequency *(rad/s)*
c	-	Velocity of light in free-space (2.998×10^8 m/s)
k	-	Wavenumber *(rad/m)*
h	-	Cutoff Wavenumber *(rad/m)*

l	-	length (m)
Z	-	Impedance (Ω)
ζ	-	Loss Term (dimensionless)
CPS	-	Coplanar Strip
EMC	-	Electromagnetic Compatibility
EME	-	Electromagnetic Emission
EMI	-	Electromagnetic Interference
EMS	-	Electromagnetic Susceptibility
EUT	-	Equipment Under Test
FCC	-	Federal Communications Commission's
FDTD	-	Finite Difference Time Domain
GTEM	-	Gigahertz Transverse Electromagnetic
IEC	-	International Electrotechnical Commission
MoM	-	Method of Moment
PCB	-	Printed Circuit Board
PEC	-	Perfect Electric Conductor
RAM	-	Radio Absorbing Material
SE	-	Shielding Effectiveness
S_E	-	Electric Shielding Effectiveness
S_M	-	Magnetic Shielding Effectiveness
TE	-	Transverse Electric
TLM	-	Transmission Line Matrix
TM	-	Transverse Magnetic

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 General

The International Electrotechnical Commission (IEC) has defined Electromagnetic Compatibility (EMC) as [1]:

"Electromagnetic Compatibility, EMC is the ability of device, equipment, or system to function satisfactorily in its environment without introducing intolerable electromagnetic disturbance to anything in that environment."

The definition of EMC implies that it is important for all electrical and electronic equipment to take into consideration of complying with the relevant EMC standards from the early stage of designing until production. In the context of Malaysian manufacturers, EMC plays a significant role in order to penetrate international markets especially the United States of America, European Union and Japan. A design engineer must understand the various techniques that can be employed to ensure compliance to EMC standards especially related to electromagnetic emission (EME) and electromagnetic susceptibility (EMS). Some important approaches that can be implemented are by reducing the loop area, filtering, grounding, bonding and shielding. Not all these measures can be implemented due to the space and circuit operation constraint but shielding can be considered as a last resort to reduce excessive emission and provide sufficient immunity to electromagnetic wave.

A system is electromagnetically compatible if it satisfies three criteria which are:

i. It does not cause interference with other systems.
ii. It is not susceptible to emission from other systems.
iii. It does not cause interference with itself.

EMC can be divided into two aspects, namely EME and EMS. EME is defined as *'the phenomenon by which electromagnetic energy emanates from a source'* [1], while EMS is defined as *'the ability of a device, equipment or system to perform without degradation in the presence of an electromagnetic disturbance'* [1]. Figure 1.1 shows the relationship between these two main aspects, where emission can have consequence both inside and outside the system containing the source of the disturbance [2]. A similar conclusion can be made for susceptibility, where a situation without any electromagnetic interference (EMI) problem inside the system is said to be intrasystem compatible. It is intersystem compatible when there are no EMI problems between systems. In order to achieve this situation, it is necessary to reduce the EME from sources that are controllable or to increase the EMS of equipment that may be affected, or to do both. The degradation of the performance of a device, transmission channel, or system caused by an electromagnetic disturbance might be occurred without EMC consciousness. However, to eliminate all possibilities of EMI by decreasing emissions and increasing susceptibility using various ways such as reducing the loop area of the circuit or use a better component could create a high cost to industry and could prevent new technologies from emerging.

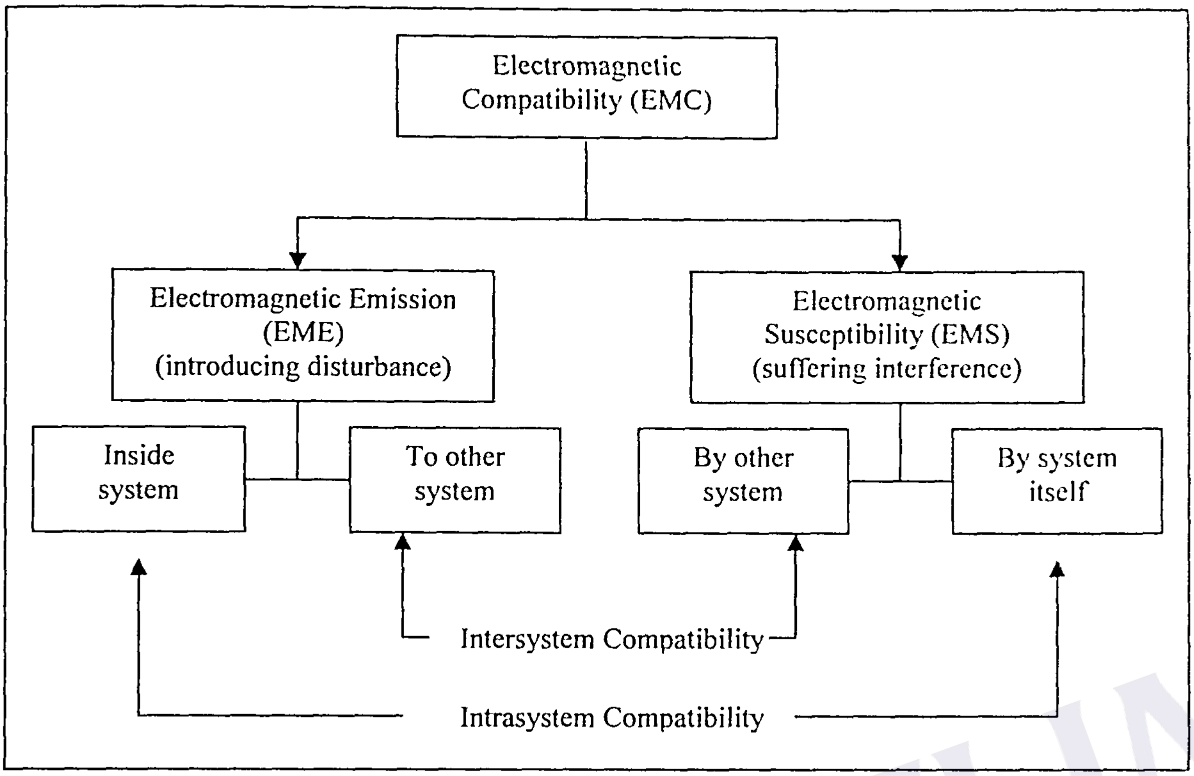

Figure 1.1: Aspects of electromagnetic compatibility [2].

The primary EMC design techniques are inclusive of electromagnetic shielding, circuit filtering, and good ground design including special attenuation to the bonding of grounding elements [3]. Figure 1.2 presents the recommended methodology of a good EMC design for a device or system [4].

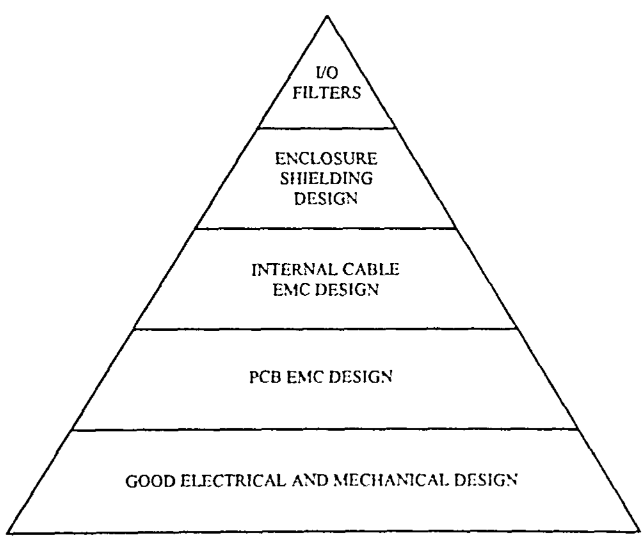

Figure 1.2: Electromagnetic compatibility design pyramid [4].

The foundation of a good EMC design is simply the application of *good electrical and mechanical design* principles. This includes reliability considerations by achieving the design specifications within acceptable tolerances, good packaging and comprehensive testing development.

Generally, the engine that drives today's electronic equipment is located on a printed circuit board (PCB). This engine is comprised of potential interference sources, as well as components and circuits which are sensitive to electromagnetic energy. Therefore, the *PCB EMC design* is the next most important consideration in EMC design. The location of active components, the routing of traces, impedance matching, grounding design, and circuit filtering are driven, in part, by EMC considerations. Certain PCB components may also require shielding.

The internal cables are generally used to connect PCBs or other internal subassemblies. The *internal cable EMC design*, including routing and shielding, is very important to the overall EMC of any given device. After the EMC design of the PCB and internal cables are complete, special attention must be given to the *enclosure shielding design* and the treatment of all apertures, penetrations and cable interfaces. Finally, consideration must be given to *filtering of input and output power and other cables.*

EMC is important for export market to anticipate and tackle problems from the beginning. In terms of product quality, it gives better functionality and customer satisfaction. In order to achieve the requirement, EMC design should be an integral part of any electronic devices or systems. Not all these measures can be implemented due to the space and circuit operation constraint. Since, this research work only concentrated on the radiated EMI, therefore, an EMC design criterion varies mostly in the enclosure shielding design [3], [5], [6]. It requires special attention since it is the last line of defense for controlling radiated EMI and providing sufficient immunity to electromagnetic wave. The shielding enclosure can be achieved by enclosing the circuit with a metallic structure without affecting the operation of the circuit. This is far more cost effective than the alternative that is attempting to achieve EMC on a finished product.

The research work presented in this thesis is to develop further understanding of the quality of shielding for rectangular metallic enclosures with apertures.

1.2 Problem Statement

Recently, new technology particularly entails the use of high speed digital circuits (HSDC), responding to the need for increased processing rates of data. The use of high speed-high edge rate digital circuits, along with the need for low power consumption, have contributed to higher EME from the circuits and increased sensitivity of the circuits or on the other, leading to EMI problems. Although the radiated EMI can be reduced significantly by taking appropriate measures at PCB level, a shielding enclosure still remains necessary and important part of most electronic systems, whereas, in compare with the qualitative design. The biggest advantage is that it can estimate the EMC performance of the product design by its shielding effectiveness (SE) [3], [5], [6]. Thus, it becomes as an effective solution to provide sufficient protection to HSDC.

The integrity of shielding enclosures for HSDC is compromised by slots and apertures for heat dissipation, CD-ROMs, input/output (I/O) cable penetration, plate-covered unused connector ports and among other possibilities. It will results in too much leakage from the shielded equipment or make the equipment susceptible to external radiation. Radiation from slots and apertures in conducting enclosures are a great concern in meeting the EMC standards (eg. CISPR 22) for radiated EMI limits.

As more high-speed electronics find their way into industrial applications, EMI is becoming a bigger issue and will degrade the performance of the shielding enclosures. Since the effects of EMI to the electronics equipment are immense, this research is performed to investigate the effect of apertures penetration to the SE of a metallic enclosure.

There are two fields involved at each point in the enclosure to give the values of SE which are electric shielding effectiveness, S_E and magnetic shielding effectiveness, S_M. At present, this research work was only concentrated on the determination of S_E in the enclosure, since it is difficult to predict the S_M due to the limitations of the enclosure sizes and instrumentations. In practical design, not all the slots and apertures are located centrally on one face due to the space limitations. Therefore, this research work was concentrated on the aperture located at off-centred positions and investigated at different aspects such as the influence of aperture and enclosure sizes, aperture shapes, aperture positions, number of apertures, and the effects of enclosure contents to ensure an optimum benefit from the metallic packaging for practical use. An improved formulation has been developed to take into consideration the contribution of higher order modes in the enclosure to provide an accurate estimation of SE.

1.3 Aim of Research

The aim of this research is to determine the electric shielding effectiveness, S_E of a metallic enclosure for off-centred apertures by using an analytical formulation and experimental measurements in order to provide simple design rules for designers of shielded enclosures.

1.4 Objectives of Research

The primary objectives of this research are:

i. To develop the analytical model of a metallic enclosure with off-centred apertures.

ii. To determine the electric shielding effectiveness, S_E of a metallic enclosure for various aperture sizes, aperture shapes, aperture locations and number of apertures by taking into account the contribution of modes higher than TE_{10} mode.

iii. To perform experimental measurements for analytical results comparison.

iv. To suggest simple design rules for shielded enclosures designers.

1.5 Scopes of Research

The research work is an extension to the approaches developed by other researchers [7]. The research is on electromagnetic shielding that is frequently used to reduce the emissions or improve the immunity of electronic equipment. The ability of a shielding enclosure to do this is characterized by its SE. A lot of research works have been carried out to estimate the SE of metallic enclosures with apertures placing centrally in one face of the enclosure [7], [8], [9]. The following scopes have been employed to ensure a well defined problem and meaningful results in order to achieve the target:

REFERENCES

[1] IEC (1989) Electromagnetic Compatibility. "International Electrotechnical Vocabulary." Chapter 161. IEC Publication 50 (161). Geneva.

[2] Goedbloed, J. (1990). "Electromagnetic Compatibility." N.J.: Prentice Hall.

[3] Paul, C.R. (1992). "Introduction to Electromagnetic Compatibility." United States: Wiley Series.

[4] Electromagnetic Compatibility Design: available at: http://www.tecknit.com/REFA_I/EMIShieldingDesign.pdf (27/02/2007)

[5] Morrison, R. (1998). "Grounding and Shielding Techniques." 4th Edition. New York: John Wiley.

[6] Weston, D.A. (2001). "Electromagnetic Compatibility Principles and Applications." 2nd Edition (Revised and Expanded). New York: Marcal Dekker.

[7] Robinson, M.P., Benson, T.M., Christopoulos, C., Dawson, J.F., Ganley, M.D., Marvin, A.C., Porter, S.J. and Thomas, D.W.P. (1998). "Analytical Formulation for the Shielding Effectiveness of Enclosures with Apertures." *IEEE Transactions on Electromagnetic Compatibility*. Vol. 40. No. 3. pp. 240-247.

[8] Olyslager, F., Laermans, E., De Zutter, D., Criel, S., De Smedth, R., Lietaert, N. and De Clercq, A. (1999). "Numerical and Experimental Study of the Shielding Effectiveness of Metallic Enclosure." *IEEE Transactions on Electromagnetic Compatibility*. Vol. 41. pp. 202-213.

[9] Sewell, P., Turner, J.D., Robinson, M.P., Thomas, D.W.P., Benson, T.M., Christopoulos, C., Dawson, J.F., Ganley, M.D., Marvin, A.C. and Porter, S.J. (1998). "Comparison of Analytical, Numerical, and Approximate Models for Shielding Effectiveness with Measurement." *IEEE Proceedings Science Measurements Technology*. Vol. 145. No. 2. pp. 61-66.

[10] Schulz, R.B. (1988). "Shielding Theory and Practice." *IEEE Transactions on Electromagnetic Compatibility*. Vol. 30. No. 3. pp.187-201 (updated from Proc. 9th Tri-Serv. Conference Electromagnetic Compatibility, Oct. 1963).

[11] Elliot, R.S. (1981). "Antenna Theory and Design." Eaglewood Cliffs, N.J.: Prentice Hall.

[12] Galejs, J. (1963). "Admittance of a Rectangular Slot which is Backed by a Rectangular Cavity." *IEEE Transactions on Antenna Propagation*. Vol. AP-11. pp. 119-126.

[13] Cockrell, C.R. (1976). "The Input Admittance of the Rectangular Cavity Backed Slot Antenna." *IEEE Transactions on Antenna Propagation*. Vol. AP-24. No. 3.pp. 288-294.

[14] Paul, C.R. and Nasar, S.A. (1987). "Introduction to Electromagnetic Fields." 2nd Edition. New York: McGraw-Hill.

[15] Hemming, L.H. (1992). "Applying the Waveguide Below Cut-Off Principle to Shielded Enclosure Design." *International Symposium on Electromagnetic Compatibility*. pp. 287–289.

[16] Balanis, C.A. (1982). "Antenna Theory Analysis and Design." New York: Harper and Row.

[17] Deshpande, M. D., Beck, F. B. and Cockrell, C. R. (1999). "Electromagnetic Shielding Effectiveness of Rectangular Enclosure with Perforated Walls." *Proceedings, 18th Digital Avionics Systems Conference*. Vol. C.2-7. pp. 1-6.

[18] Mendez, H.A. (1978). "Shielding Theory of Enclosures with Apertures." *IEEE Transactions on Electromagnetic Compatibility*. Vol. 20. pp. 296–305.

[19] Cerri, G., De Leo, R., and Primiani, V.M. (1992). "Theoretical and experimental evaluation of the electromagnetic radiation from apertures in shielded enclosures." *IEEE Transactions on Electromagnetic Compatibility*. Vol. 34, pp. 423–432.

[20] Belokour, I., LoVetri, J. and Kashyap, S. (2000) "Shielding Effectiveness Estimation of Enclosures with Apertures." *IEEE Electromagnetic Compatibility Symposium Proceedings*. pp. 855-860.

[21] Klinkenbusch, L. (2005). "On the Shielding Effectiveness of Enclosures." *IEEE Transactions on Electromagnetic Compatibility*. Vol. 47. pp. 589-601.

[22] Khan, Z (2005). "Shielding Effectiveness of Metallic Enclosures at Oblique and Arbitrary Polarizations." *IEEE Transactions on Electromagnetic Compatibility*. Vol. 47. No. 1. pp.112-130.

[23] Rajamani, V., Bunting, C.F., Deshpande, M.D. and Khan, Z.A. (2006). "Validation of Modal/MoM in Shielding Effectiveness Studies of Rectangular Enclosures with Apertures." *IEEE Transactions on Electromagnetic Compatibility*. Vol. 48. No. 2. pp. 348-353.

[24] Marvin, A.C. and Cui, Y. (2005). "Towards Evaluating the Shielding of Enclosures with Contents at Frequencies above 1 GHz." *International Symposium on Electromagnetic Compatibility*. Vol. 1. pp. 200-205.

[25] Olyslager, F. and Fostier, J. (2006). "Fast and Accurate Evaluation of the Shielding Effectiveness of Complex Enclosures." *17th International Zurich Symposium on Electromagnetic Compatibility*. Singapore. pp. 30-33.

[26] Shen, Z. (2006). "Shielding Effectiveness of Cylindrical Enclosures with Annular Ring Apetures." *17th International Zurich Symposium on Electromagnetic Compatibility*. Singapore. pp. 38-41.

[27] Kraft, C. H. (1994). "Modeling Leakage through Finite Apertures with TLM." *IEEE International Symposium on Electromagnetic Compatibility*. Chicago, IL. pp. 73–76.

[28] Gupta, K.C., Garg, R. and Bahl, I.J. (1979). "Microstrip Lines and Slotlines." Norwood, MA: Artech House. Chapter 7. 375-456.

[29] Ramo, S., Whinnery, J.R. and Van Duzer, T. (1994). "Fields and Waves in Communication Electronics." 3rd Edition. John Wiley & Sons, Inc.

[30] Collin, R. (1960). "Field Theory of Guided Waves." McGraw Hill Book Company. Inc. New York.

[31] Dawson, J.F., Ahmadi, J. and Marvin, A.C. (1992). "Reduction of radiated emissions from apertures in resonant enclosures by the use of absorptive materials." *8th International Conference Electromagnetic Compatibility*. Edinburgh, U.K. pp. 207–212.

[32] Woods, I.D. (1971). "Admittance Transformation using Precision Air-Dielectric Coaxial Lines and Connectors." *Proceedings Institute Electrical Engineering*. Vol. 118. pp. 1667–1674.

[33] Turner, J.D., Benson, T.M., Christopoulos, C., Thomas, D.W.P., Robinson, M.P., Dawson, J.F., Ganley, M.D., Marvin, A.C. and Porter, S.J. (1996). "Characterization of the Shielding Effectiveness of Equipment Cabinets Containing Apertures." *International Symposium on Electromagnetic Compatibility*. Rome, Italy. pp. 574–578.

[34] White, D. R. J. (1980). "A Handbook on Electromagnetic Shielding Materials and Performance." *Interference Control Technology*. Gainesville, FL.

[35] White, D. R. J. and Mardiguian, M. (1988). "Handbook Series on Electromagnetic Interference and Compatibility- Vol. 3: Electromagnetic Shielding." *Interference Control Technology*. Gainesville, FL.

[36] White, D. R. J. (1996). "A Handbook on shielding design methodology and procedures." *Interference Control Technology*. Gainesville, FL.

[37] Li, M., Nuebel, J., Drewniak, J.L., Daroff, R., Hubing, T. and Van Doren, T. (2000). "EM1 from Cavity Modes of Shielding Enclosures - FDTD Modeling and Measurements." *IEEE Transaction On Electromagnetic Compatibility*. Vol. 42. No. 1. pp. 29-38.

[38] Beranek, L. L. and V´er, I. L. (1992). "Noise and Vibration Control Engineering-Principles and Applications." New York: Wiley.