Analysis of the Response of Microstrip Line in Shielding Cavity by Electromagnetic Topological Approach

Liping Wang
PLA Information Engineering University, Zhengzhou 450002, Henan, China; The Third Hospital of PLA, Baoji 721000, Shanxi, China

Dongfang Zhou*
PLA Information Engineering University, Zhengzhou 450002, Henan, China;

Lipeng Ma*
66131 Forces, Baoding 071000, Hebei, China;

Guodong Zhang*
73698 Forces, Fuzhou 310002, Fujian, China
E-mail: 934922291@qq.com

Abstract
In order to solve the problems of terminal responses of the microstrip line, this paper presents the semi-analytical mixed method based on the topology network. First, it needs to build electromagnetic topology model of apertures, cavity and microstrip; Then, the apertures can be converted to the equivalent magnetic currents, and the coupling electromagnetic field is expressed by using these magnetic currents and the Green’s functions; Finally, the BLT equation is used to calculate the voltage and current, that is, the microstrip line’s coupling terminal response. The validity of the method is proved by comparing with measured results and other methods. Numerical results show that the response of microstrip line reaches its peak value near the slot and cavity resonance. Moreover, the microstrip line is nearer apertures and the pulse width is narrower, the coupling voltage of the microstrip is bigger. The analytic results give reference to the design of the protection of electronic equipment against the external source and effective evaluation.

Key words: Electromagnetic Topology, the Green’s Functions, Transmission Line Theory, Microstrip Line

1. INTRODUCTION
At present, the research on the electromagnetic coupling microstrip line terminal response and hole and shielding effectiveness is much more (Zhou and Zhang, 2016; Zhou and Zhang, 2014; Zhang and Wang, 2016), but the research on perforated shielding cavity body electromagnetic coupling microstrip line terminal response is less, and mostly study is focus on port voltage response of the microstrip line the plane wave in free space (Yu and Wang, 2011; Atrous and Baudry, 2008), calculation for bare coupled microstrip line terminal response is relatively simple, the electronic system in the actual have shielding shell, because of the shielding layer is introduced, greatly increased the complexity of the calculation and analysis. Also have some references to calculate the shielding body coupled terminal response of the double wire, but they simply to calculate the coupling of a transmission line terminal frequency domain waveform (Atsutake and Okada, 2016); Wang theoretically analyzed the effectiveness of cavity body with PCB in it (Wang and Gao, 2008); Huang using FDTD electromagnetic field simulation software analyzed the shielding effectiveness to cavity body of parameters in medium plate and hole cavity position (Huang and Zhang, 2012). Most of these research are based on the electromagnetic simulation software to analysis cavity shielding effectiveness, without considering the cavity microstrip line in the body, on the other hand, this method have complex calculations and difficult to change the model parameters.

This paper aim at coupling terminal response of microstrip line in the shielding cavity, proposed a semi-analytical hybrid algorithm, the electromagnetic topology theory, combined the transmission line theory, topological theory of electromagnetic and the green's function in the body cavity, through the study for coupling terminal responds of microstrip line in perforated seam cavity, we can get general rules of shielded microstrip line coupling cavity, and established theoretical foundation of electromagnetic compatibility and effectiveness evaluation for the study of high power microwave pulse under the irradiation of complex microwave circuit.

2. ESTABLISHMENT of the ELECTROMAGNETIC TOPOLOGY MODEL
Assuming that the shielding cavity size is $a \times b \times d$, there is a crack in cavity anterior wall on $z = 0$, aperture size is $l \times w$, printed circuit board is located in the shielding cavity, length of microstrip line is $L$, as shown in figure 1.
Figure 1. The microstrip lines in the shielding cavity with apertures

When the electromagnetic wave incident in shielding cavity perforated seam, and electromagnetic enter the shielding cavity body through the hole, then resonance occurs inside the cavity, so it is possible bring interference or damage to internal circuit. Then analysis the electromagnetic topology, and then to set up the electromagnetic topological model for shielding cavity coupling microstrip lines as shown figure 2, which consists of three transmission lines, where $T_1$ is virtual, $T_2$, $T_3$ is a transmission line for microstrip transmission lines and nodes $J_1$ represent hole seam, nodes $J_2$ represent midpoint of microstrip line, node $J_3$, $J_4$ is the terminal of the microstrip line.

3. ESTABLISHMENT of the CALCULATION

The basic idea of this algorithm is, sew hole equivalent to magnetic fluid, then use the method of green's function to solve the electric field distribution in the body, and combining the network BLT equation to solve the voltage current of each node, finally we can get the coupling microstrip line terminal response anywhere.

3.1. Equivalent Magnetic Current

With the advancement in networking and multimedia technologies enables the distribution and sharing of multimedia content widely. In the meantime, piracy becomes increasingly rampant as the customers can easily duplicate and redistribute the received multimedia content to a large audience. Insuring the copyrighted multimedia content is appropriately used has become increasingly critical.

Through the magnetization coefficient of hole, we can get the relationship of short circuit magnetic and magnetic moment vector. magnetic moment vector $\vec{m}$ is as follows

$$\vec{m} = \alpha \vec{H}_n$$

(1)

Where $\alpha$ is susceptibility, $\vec{H}_n$ is tangential magnetic field when narrow slit is filling with metal, also known as a short circuit magnetic field.

In infinite conductor plane, if the plane wave vertical incidence conductor, the short circuit is equal to twice the incident field, it is to say $H_n = 2|H_0| = 2|E_0|/\eta_0$, where $H_0$ is incident magnetic field component, $E_0$ is incident electric field component, $\eta_0$ is vacuum wave impedance. $\alpha$ uses the revised magnetization coefficient as literature(Salah B. and Lionel P., 2002).
Based on the relationship of magnetic flux density and magnetic moment vector, we can get the equivalent magnetic current of hole joints.

\[ \mathbf{J}_m = -j\omega \mu_0 \alpha \mathbf{H}_v \]  

Now we solving the electric field distribution in magnetic current excitation cavity. Firstly, introduces the green's function of unit magnetic flux which located inside the cavity, then converted to the case where magnetic flux in cavity wall, as shown in figure 3.

![Figure 3. Magnetic flux which located inside the cavity and in cavity wall](image)

Electric field of point \((x, y, z)\) of unit of magnetic flux excitation chamber in the body cavity in X direction is:

\[
E_x = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{\cos(\beta z) \sin(\beta (z - d))}{\beta \sin d} \cdot \frac{1}{a b} \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{1}{a b} \cdot \sin(\frac{m\pi x}{a}) \cos(\frac{n\pi y}{b}) \cdot \sin(\frac{m\pi x}{a}) \cos(\frac{n\pi y}{b}) \cdot 1_{z<z_s} \]

\[
E_x = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{\cos(\beta z) \cos(\beta (z - d))}{\beta \sin d} \cdot \frac{1}{a b} \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{1}{a b} \cdot \sin(\frac{m\pi x}{a}) \cos(\frac{n\pi y}{b}) \cdot \sin(\frac{m\pi x}{a}) \cos(\frac{n\pi y}{b}) \cdot 1_{z<z_s} \]

Where, \( \varepsilon_n =\) 0 \( m=0 \), \( \varepsilon_n =\) 1 \( n=0 \), \( \varepsilon_n =\) 2 \( n \neq 0 \).

Above expression is electric field intensity of unit magnetic flow excitation, for magnetic current is \( \mathbf{J}_m \), we can get the electric field intensity by multiplied \( \mathbf{J}_m \) with above formula, and get the actual electric field in cavity, \( m, n \) take the top ten, and we can get the more accurate solutions. When \( z_s = 0 \) for above formula, the electric field component chamber just take expression \( z > 0 \), which indicates that magnetic flux in cavity wall. If there are multiple narrow cavity wall, field quantities of multiple slit can be calculated separately, then execution vector superposition, this approach ignores the mutual coupling between the slit.

### 3.2. Each Parameter Matrix of the Network a Transmission Line is Determined

As shown in figure 2, transmission line network consists of \( T_1, T_2, T_3 \), voltage and current at the ends of transmission line \( T_i \) is \( V_{i1}, V_{i2}, I_{i1}, I_{i2} \), and written in matrix form according to the node order, then the vector of voltage and current for the entire transmission line network is

\[
V_L = \begin{bmatrix} V_{11} & V_{21} & V_{31} & V_{12} & V_{22} & V_{32} \end{bmatrix}^T
\]

\[
I_L = \begin{bmatrix} I_{11} & I_{21} & I_{31} & I_{12} & I_{22} & I_{32} \end{bmatrix}^T
\]

Transmission line network node voltage current BLT equation is
\[ V_i = (U + \rho)(-\rho + \Gamma)^{-1}S \]
\[ I_i = Y(U - \rho)(-\rho + \Gamma)^{-1}S \]  

(7)

Where U is 6×6 unit matrix, r and \( \Gamma \) are scattering matrix and transmission matrix in order of node block respectively, Y is features ultra-admittance matrix in order of node, S is 6-dimensional excitation source vector in the order of node, we can get the voltage and current of each node by solve the network BLT equation. Here we give the method to determine each parameter matrix of network BLT equation.

\( J_2 \) is the midpoint of microstrip line, which is an ideal node, according to literature (Song H. and Zhou D. F., 2008), the scattering matrix is

\[
\begin{bmatrix}
-Y_g & Y_g - 2Y_e & -Y_g \\
2Y_e + Y_g & 2Y_e + Y_g + 1 & 2Y_e + Y_g + 1 \\
-2Y_e + Y_g + 1 & Y_e - 2Y_g & Y_e - 2Y_g \\
-2Y_g & 2Y_e + Y_g & 2Y_e + Y_g + 1 \\
\end{bmatrix}
\]  

(8)

\( Y_g \) is Waveguide characteristic admittance, \( Y_e \) is Characteristic admittance of microstrip line. Characteristic impedance of transmission pipeline \( T_1 \) equivalent to characteristic impedance \( Z_g \), node \( J_1 \) equivalent to termination aperture impedance \( Z_{ap} \), so the reflection coefficient of node \( J_1 \) is

\[ \rho_1 = \frac{Z_{ap} - Z_g}{Z_{ap} + Z_g} \]  

(9)

The reflection coefficient of microstrip line terminal \( J_3, J_4 \) is defined as:

\[ \rho_2 = \frac{Z_{12} - Z_e}{Z_{12} + Z_e} \quad \rho_4 = \frac{Z_{12} - Z_e}{Z_{12} + Z_e} \]  

(10)

Then the scattering matrix of whole network is:

\[ \rho = \begin{bmatrix} \rho_1 & \rho_2 \\ \rho_4 & \rho_3 \end{bmatrix} \]  

(11)

Network transmission constant matrix is defined as:

\[ \Gamma = \begin{bmatrix} 0 & \text{diag}[e^{\gamma_h}] \\ \text{diag}[e^{\gamma_h}] & 0 \end{bmatrix}, \quad \text{diag}[e^{\gamma_h}] = \begin{bmatrix} e^{\beta_p} \\ e^{\beta_p/2} \end{bmatrix} \]  

(12)

Where waveguide propagation constant is \( k_g = k_0 \sqrt{1 - (\lambda / 2 \alpha)} \), \( g \) is transmission constant of microstrip line.

Arrangement the characteristic admittance matrix of a transmission line in order of nodes, we can get:

\[ Y = [Y_g \, Y_e \, Y_e \, Y_g \, Y_e \, Y_e]^T \]  

(13)

Excitation source vector of transmission network are as follows

\[ S = [S_{11} \, S_{21} \, S_{31} \, S_{12} \, S_{22} \, S_{32}]^T \]  

(14)

Using the field coupling Agrawal model (Rachidi, 2012) to solve on a transmission line equivalent excitation source.

\[ \begin{bmatrix} S_{11} \\ S_{22} \end{bmatrix} = \begin{bmatrix} \frac{1}{2} \int_{-W}^{W} e^{jy/2} V_a(y)dy - \frac{V_2}{2} + \frac{V_2}{2} e^{j\pi/2} \\ -\frac{1}{2} \int_{-W}^{W} e^{j(y/2-y)} V_a(y)dy + \frac{V_2}{2} e^{-j\pi/2} - \frac{V_3}{2} \end{bmatrix} \]  

(15)

(16)

\[
\begin{pmatrix}
S_{31} \\
S_{32}
\end{pmatrix} = \frac{1}{2} \int_{y_0}^{y_1} e^{j\gamma y} V_a(y) dy - \frac{V_4}{2} e^{j\gamma b} + \frac{V_4}{2} e^{j\gamma/2} - \frac{V_4}{2}
\]

\begin{align}
V_2 &= -\int_{x_0}^{x_1} E_{e}^{inc}(x_0, y, z) dz, \\
V_3 &= -\int_{x_0}^{x_1} E_{e}^{inc}(x_0, y, z) dz, \\
V_4 &= -\int_{x_0}^{x_1} E_{e}^{inc}(x_0, y, z) dz,
\end{align}

\[
V_a = E_{e}^{inc}(x_0, y, z_0) = E_{e}^{inc}(x_0, y, z_0).
\]

The endpoint coordinates of microstrip line is \((x_0, y_0, z_0)\) and \((x_0, y_0, z_0)\), the coordinates of the front-end and back-end point for printed circuit board in the direction of \(z\) is \(z_0, z_0\).

3.3. Calculating Cavity Shielding Effectiveness and Terminal Response

As shown in figure 2, transmission line network consists of \(T_1, T_2, T_3\), the voltage and current at the ends of transmission line \(T\) is \(V_1, V_2, I_1, I_2\), and written in matrix form according to the node order, then the vector of voltage and current for the entire transmission line network is

Using network BLT equation established above, we can calculate the voltage and current of any node, and also can calculate the shielding effectiveness of midpoint for printed panels (that is point P of the node \(J_z\)).

Firstly using BLT equation to calculate the voltage \(V_{12}\), then according to the conversion relationship between voltage and the electric field inside the waveguide

\[
E_y = V_{12} \sqrt{\frac{2}{ab}}
\]

Consider holes exist slot and the waveguide discontinuity, transformation ratio

\[
R = \sqrt{\frac{ab}{wl}}
\]

The electric field of observation point is as follows

\[
E_{py} = E_y \cdot R = V_{12} \sqrt{\frac{2}{ab}} \cdot \sqrt{\frac{ab}{wl}} = V_{12} \frac{2}{wl}
\]

Above is suitable for the hole length \(l\) is much bigger than the width \(w\). If there are multiple hole sew on the cavity wall, the voltage of observation point is the superposition of each hole sew.

\[
V_{32} = \sum_i V'_{32}
\]

So the electric field is as follows:

\[
E_{py} = V_{12} \sqrt{\frac{2}{S_h}}
\]

\(S_h\) is the total area of the hole array.

Electric field shielding effectiveness of point P is defined as:

\[
SE = -20 \lg \left| \frac{E_p}{E_0} \right|
\]

\(E_p\) is the Electric field amplitude for point P in the body cavity, \(E_0\) is the electric field when cavity does not exist.

4. SIMULATION CALCULATIONS and ANALYSIS

4.1. Proof of Algorithm

To verify the correctness of this algorithm, the parameter set is consistent with the literature (Rao Y. P. and Zhou D. F., 2008), shielding cavity size is \(222\text{mm} \times 55\text{mm} \times 146\text{mm}\), the center of the front wall hole size is \(100\text{mm} \times 5\text{mm}\). Figure 4 shows the found contrast curve of shielding effectiveness value of log-periodic antenna. We set the metal rectangular cavity size to size \(300\text{mm} \times 120\text{mm} \times 300\text{mm}\) (computer chassis size), from the center of front wall hole size remains the same. Figure 5 is the method to calculate shielding effectiveness curve of cavity center by equivalent transmission line, cavity Green function method and transmission line network BLT equation method.
From the simulation curve of figure 4 and figure 5, we can see the results proposed in this paper is very consistent with actual measured value, equivalent transmission line method and cavity Green function method; And the Hybrid algorithm calculations proposed in this paper is much closer than cavity green function method, but the result of equivalent transmission line at low frequencies is much smaller than other two method. Theoretically Low-frequency electromagnetic waves is not easily coupled to the cavity.so the presented analytical hybrid algorithm is more reasonable.

In addition, can be seen from the figure also, simulation curve of this algorithm in the resonance frequency points of the shielding effectiveness of the SE value is improved, because the cavity body exist printed circuit board, which suppression resonant frequency of the cavity, this rule is consistent with literature(Wang and Gao, 2008).

4.2. HPM Pulse Seam with Rectangular Cavity Coupling Microstrip Line Analysis

Analysis of Gaussian Pulse

Using gaussian pulse simulate high power microwave pulse, the pulse amplitude is set to 1000V/m , \( t_0 = 2 \times 10^{-9} \), \( \tau = 0.5 \times 10^{-9} \). With the steep rising and very narrow pulse width, can better simulate ultra-wideband electromagnetic pulse characteristics. Rectangular cavity size is set to \( 300mm \times 120mm \times 300mm \), the front wall with the hole seam \( 100mm \times 5mm \), printed panels in the width of \( W = 3.12mm \), length is \( L = 100mm \), thickness is \( t = 0.5mm \), height of medium plate \( h = 2mm \), permittivity is \( \varepsilon'_r = 4.7 \), drain conductance is \( \sigma' = 5 \times 10^{-5} \), terminal load of microstrip line \( R_{in}, R_{out} \) are 50Ω. When microstrip line is placed in the center of the cavity, the calculate result of coupling terminal responds is as figure 6.
From figure 6 shows terminal coupled voltage of microstrip line is rapid oscillation with time, and coupling occurs between gauss pulse and belt joint, can excite large number of high-order in shielded cavity, it is to say, generating certain frequencies of the resonance electric field component, so that the coupling terminal responds of the microstrip line is vary with the resonant field, but overall trend it is attenuation with time. Figure 6 of the experimental results of the calculation results with the literature (Rao Y. P. and Zhou D. F., 2008) and literature (Li L. H. and Liao C., 2008) in the law of the numerical simulation results have consistency. As shown in fig.6, voltage with the order of several volts will be built on the microstrip line in the shielding cavity when exited by Gaussian pulse with the electric field strength of 1 kV/m. This will disturb ordinary electric equipment or sensitive components and will damage the equipment if the strength field of the pulse enhances.

![Figure 6](image)

**Figure 6.** Time-domain waveform of microstrip line’s coupling terminal responds

**Analysis of Nuclear Electromagnetic Pulse**

Nuclear electromagnetic pulse (EMP) comes from nuclear explosion. It has ultrafast rise time and is the main source of threat to electric equipment. The peak field strength of the pulse reaches 10~100kV/m and the frequency covers from ultra-long wave to low band microwave. Nuclear EMP brings serious threat to the radio communication system, navigation system, broadcast system and so on. Nuclear EMP can be described by double-exponential pulse function as follow:

\[
E_{\text{inc}} = 10^4 \left( e^{-6.666 \times 10^7 t} - e^{-4 \times 10^7 t} \right)
\]  

(24)

The effect of nuclear EMP irradiation on the microstrip line shielding is analyzed and the results are given in Fig. 7. The coupling terminal voltage can decrease by one order of magnitude when shielding cavity is utilized, as shown in the figure. The computational results show that shielding cavity can reduce the strength of the incident EMP remarkably. The same law is for the variation of waveform of the coupling terminal voltage changes and the resonant field due to generation of resonant field in the aperture cavity caused by incident EMP. The printed circuit board will suffer from strong surge when exposed to EMP directly. It is necessary to take effective measures to protect the sensitive circuit according to the above analysis.

![Diagram](image)
5. CONCLUSIONS

Electromagnetic topology theory can make the problem simple, cavity green's function method can calculate shielding effectiveness of cavity, BLT can rapid calculate nodes response of model, this paper complex three methods or theory’s advantages and disadvantages, proposed a semi-analytical hybrid algorithm to analysis coupling terminal responds between gaussian pulse and microstrip line with seams cavity, overcome the shortcomings of simulation software modeling to meshing and large computation. This study will lay a foundation for effect analysis at system level. Theoretical analysis and simulation also verify the correctness of this algorithm, provide some reference to enhance anti-electromagnetic pulse strike capability for electronic systems, next we will consider coupling problem of microstrip line with complex structure.

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REFERENCES


