Analysis of Field-to-Transmission Line Coupling inside a Reverberation Chamber based on Mode Expansion Method

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***Abstract*—In this paper, the electromagnetic (EM) field distribution inside a reverberation chamber (RC) is constructed by Monte Carlo simulation based on mode expansion method (MC_MEM). This method provides the position information of sampling points inside a RC based on mode theory of resonant cavities. Then the current responses of a single transmission line (TL) with terminal loads located inside a RC are calculated to verify the effectiveness of MC_MEM. By comparing current responses of different TL structures, the statistical uniformity of EM field distribution inside a RC can be illustrated. And these results could provide more information about EM environment inside RC and some guidelines for TLs arrangement.**

Keywords—electromagnetic coupling; monte carlo simulation; transmission line; mode expansion method; reverberation chamber

I. Introduction

Reverberation chambers (RCs) have been deeply researched as an environment for electromagnetic compatibility (EMC) testing and other electromagnetic (EM) investigations. Analysis methods have been established to describe the statistical characteristics of EM field inside a RC, such as plane wave integral (PWI) representation[1]. And deterministic method like finite difference time domain (FDTD) is adopted to analyze susceptibility tests in RCs[2]. However, due to immense computational cost and high frequency response sensitivity (HFRS) of full wave analysis methods, deterministic methods are not suitable to deal with electrically large problems[3]. Therefore, another alternative statistical model, Monte Carlo simulation based on mode expansion method (MC_MEM), is proposed to construct EM field distribution inside a RC[4]. Based on mode theory of resonant cavities, MC_MEM contains the structural details of a RC which are ignored in PWI method. For example, the boundary fields inside a RC can be intrinsically described by MC_MEM though they have been discussed by PWI method based on boundary conditions[5][6].

In this paper, MC_MEM is adopted to thoroughly obtain the EM field distribution characteristics related to positions of sampling points. Then the current responses of internally installed equipment, a single transmission line (TL) with loads at both ends, are calculated to illustrate the effectiveness of MC_MEM.

II. Monte Carlo Mode Expansion Method to Construct Electric Field inside a Reverberation Chamber

While RC properly working, plenty of modes are excited simultaneously. The interior electric field can be constructed by superposition of various mode fields with corresponding weight coefficients. This physical process can be modeled with (1) and (2)

$$E_{x,y,z} = \sum_{(m,n,p)\in\Omega_{te}} \delta_{mnp\_te} E_{mnp\_te\_x,y,z} + \sum_{(m,n,p)\in\Omega_{tm}} \delta_{mnp\_tm} E_{mnp\_tm\_x,y,z} \quad (1)$$

$$H_{x,y,z} = \sum_{(m,n,p)\in\Omega_{te}} \delta_{mnp\_te} H_{mnp\_te\_x,y,z} + \sum_{(m,n,p)\in\Omega_{tm}} \delta_{mnp\_tm} H_{mnp\_tm\_x,y,z} \quad (2)$$

where $E_{x,y,z}$ / $H_{x,y,z}$ is the electric/magnetic field of three (x,y,z) orthogonal components, δ_{mnp_te} and δ_{mnp_tm} are the complex amplitude weight coefficients of the corresponding resonant mode, Ω_{te} and Ω_{tm} are the ranges of mode index (m,n,p), E_{mnp_te} and E_{mnp_tm} are the electric field components of different transverse electric (TE) and transverse magnetic (TM) modes. While mode stirrer rotating, the amplitudes and phases of the resonant modes are randomly varying. This randomness can be represented in MC_MEM by assuming that δ_{mnp_te} and δ_{mnp_tm} are random variables, more specifically, generating random numbers which obey U(-1,1) as their real and imaginary parts.

According to mode theory of resonant cavities[7], the TE and TM electric field at each axis (x,y,z) direction can be obtained from (3) to (8)

$$E_{xmnp}^{TE} = -\frac{i\omega_{mnp}\mu k_y H_0}{k_{mnp}^2 - k_z^2} \cos\frac{m\pi x}{a} \sin\frac{n\pi y}{b} \sin\frac{p\pi z}{c} \quad (3)$$

$$E_{ymnp}^{TE} = \frac{i\omega_{mnp}\mu k_x H_0}{k_{mnp}^2 - k_z^2}\sin\frac{m\pi x}{a}\cos\frac{n\pi y}{b}\sin\frac{p\pi z}{c} \quad (4)$$

$$E_{zmnp}^{TE} = 0 \quad (5)$$

$$E_{xmnp}^{TM} = -\frac{k_x k_z E_0}{k_{mnp}^2 - k_z^2}\cos\frac{m\pi x}{a}\sin\frac{n\pi y}{b}\sin\frac{p\pi z}{c} \quad (6)$$

$$E_{ymnp}^{TM} = \frac{k_y k_z E_0}{k_{mnp}^2 - k_z^2}\sin\frac{m\pi x}{a}\cos\frac{n\pi y}{b}\sin\frac{p\pi z}{c} \quad (7)$$

$$E_{zmnp}^{TM} = E_0 \sin\frac{m\pi x}{a}\sin\frac{n\pi y}{b}\cos\frac{p\pi z}{c} \quad (8)$$

where a , b , c are cavity dimensions, ω_{mnp} is angular frequency, μ is permeability of free space. And $k_x = m\pi/a$, $k_y = n\pi/b$, $k_z = p\pi/c$, $k_{mnp}^2 = k_x^2 + k_y^2 + k_z^2$. E_0 is an arbitrary constant in V/m, and $H_0 = E_0/\eta$, where η is the wave impedance.

According to (1) to (8), the electric field value of each component at any positions inside a RC can be constructed. The effectiveness of MC_MEM to statistically describe EM field distribution inside a RC can be verified by probability density functions (PDFs) of electric field components[4]. It also can be further verified through the responses of equipment located inside a RC. In the following sections, coupling between field and a single TL with terminal loads inside a RC are mainly discussed.

III. FIELD-TO-TRANSMISSION LINE COUPLING INSIDE A REVERBERATION CHAMBER

In this section, the responses of a single TL inside a RC are calculated by MC_MEM. The basic configuration of field-to-transmission line coupling model is shown in Fig.1. The length of TL is L , the radius is r , the height between metallic wall and TL is h , the terminal loads are Z_1 and Z_2 respectively. Based on BLT equation formed with Agrawal coupling formulations[8], the current of terminal loads $I(0)$ and $I(L)$ are

$$\begin{Bmatrix} I(0) \\ I(L) \end{Bmatrix} = \frac{1}{Z_c}\begin{bmatrix} 1-\rho_1 & 0 \\ 0 & 1-\rho_2 \end{bmatrix}\begin{bmatrix} -\rho_1 & e^{\gamma L} \\ e^{\gamma L} & -\rho_2 \end{bmatrix}^{-1}\begin{Bmatrix} S_1 \\ S_2 \end{Bmatrix} \quad (9)$$

where the equivalent sources vector are

$$\begin{Bmatrix} S_1 \\ S_2 \end{Bmatrix} = \frac{1}{2}\begin{Bmatrix} \int_0^L e^{\gamma z} E_z(0,h,z)dz + \int_0^h E_y(0,y,0)dy - e^{\gamma L}\int_0^h E_y(0,y,L)dy \\ -e^{\gamma L}\int_0^L e^{-\gamma z} E_z(0,h,z)dz - e^{\gamma L}\int_0^h E_y(0,y,0)dy + \int_0^h E_y(0,y,L)dy \end{Bmatrix} \quad (10)$$

and the TL reflection coefficients ρ_1 and ρ_2 are

$$\rho_1 = (Z_1 - Z_c)/(Z_1 + Z_c) \quad (11)$$

$$\rho_2 = (Z_2 - Z_c)/(Z_2 + Z_c) \quad (12)$$

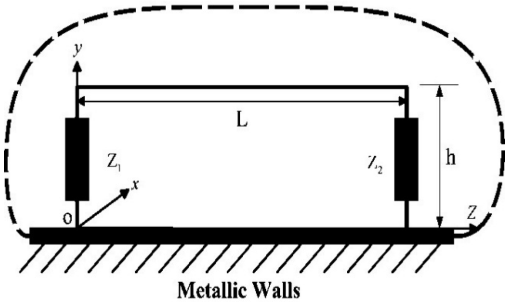

Fig. 1. Field-to-transmission line coupling configuration.

where Z_c is characteristic impedance of TL, Z_1 and Z_2 are terminal loads, γ is the propagation constant of TL, $E_y(\bullet)$ and $E_z(\bullet)$ are tangential electric field on TL. In order to simplify the equations, some variables are defined below

$$P = P_y^1 + P_z + P_y^2 \quad (13)$$

$$Q = Q_y^1 + Q_z + Q_y^2 \quad (14)$$

where

$$P_y^1 = -\frac{1}{2}\int_0^h E_y(0,y,0)dy \quad (15a)$$

$$P_y^2 = \frac{1}{2}e^{\gamma L}\int_0^h E_y(0,y,L)dy \quad (15b)$$

$$P_z = -\frac{1}{2}\int_0^L e^{\gamma z} E_z(0,h,z)dz \quad (15c)$$

$$Q_y^1 = -\frac{1}{2}\int_0^h E_y(0,y,0)dy \quad (16a)$$

$$Q_y^2 = \frac{1}{2}e^{-\gamma L}\int_0^h E_y(0,y,L)dy \quad (16b)$$

$$Q_z = -\frac{1}{2}\int_0^L e^{-\gamma z} E_z(0,h,z)dz \quad (16c)$$

According to (9) to (16), the current responses of a single TL can be obtained as (17) and (18)

$$I(0) = \frac{1}{Z_c}\frac{1-\rho_1}{e^{\gamma L} - \rho_1\rho_2 e^{-\gamma L}}\left(e^{\gamma L}Q - \rho_2 e^{-\gamma L}P\right) \quad (17)$$

$$I(L) = \frac{1}{Z_c}\frac{1-\rho_2}{e^{\gamma L} - \rho_1\rho_2 e^{-\gamma L}}\left(\rho_1 Q - P\right) \quad (18)$$

$I(0)$ and $I(L)$ is the response to single mode electric field illumination. With each rotation angle inside a RC, multiple modes are excited simultaneously. Therefore, the total current response should be considered as under the illumination by electric field which is produced by every resonant mode multiplying by the corresponding mode weights. Therefore, MC_MEM is adopted to solve it. We assume that the number of rotation angle is M , and the number of considered modes is N at each rotation angle. In this paper, 500 rotation angles are set as the value of M . The mode numbers N for each frequency is obtained by (19)

$$N(f)=\frac{8\pi}{3}abc\frac{f^3}{v^3}-(a+b+c)\frac{f}{v}+\frac{1}{2} \quad (19)$$

where f is the operating frequency, v is the speed of light in free space. While the mode stirrer at the m th rotation angle, the total current response of the TL $I_m^t(0)$ and $I_m^t(L)$ are

$$I_m^t(0)=\sum_{n=1}^{N} I_n(0) \quad (20)$$

$$I_m^t(L)=\sum_{n=1}^{N} I_n(L) \quad (21)$$

where $I_n(0)$ and $I_n(L)$ is the current response to the n th mode field. Then the total current response can be obtained through the ergodicity of all rotation angles

$$\langle I(0)\rangle=\frac{1}{M}\sum_{m=1}^{M} I_m^t(0) \quad (22)$$

$$\langle I(L)\rangle=\frac{1}{M}\sum_{m=1}^{M} I_m^t(L) \quad (23)$$

The example for RC and TL structural configuration is shown in Fig.2. The TL is uniform lossless and situated above a perfectly conducting wall of a RC. The structural parameters of RC and TL are given in Table Ⅰ.

TABLE I. STRUCTURAL PARAMETERS OF RC AND TL

Parameters	RC			TL			Loads	
	a	*b*	*l*	*h*	*R*	*L*	Z_1	Z_2
Value	2.74m	3.05m	4.75m	0.03m	0.005m	0.5m	50 Ω	50 Ω

The current response of TL at terminal load Z_1 is shown in Fig.3.

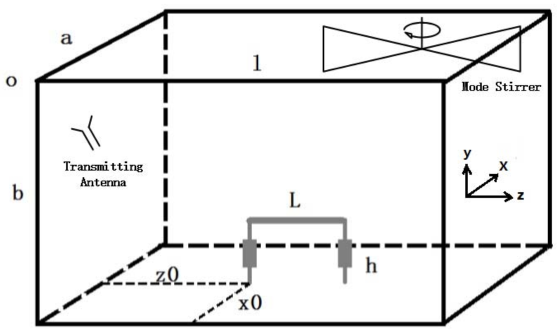

Fig. 2. Configuration of RC and TL.

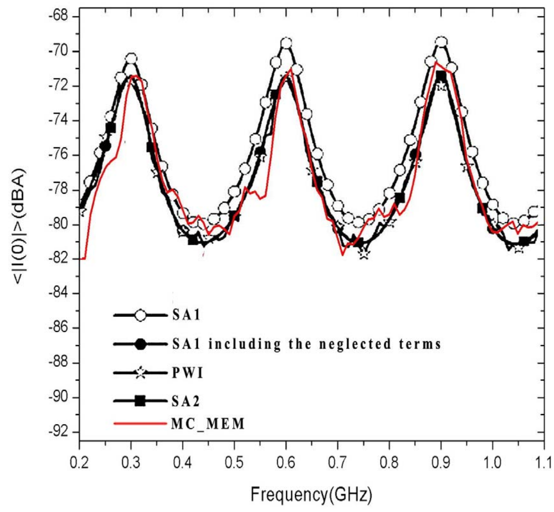

Fig. 3. Currten response of terminal load Z_1 compared with results in [9].

The black curves in Fig.3 are the current responses calculated by solutions based on PWI method[9]. The red curve obtained by MC_MEM method agrees with them, which illustrates the effectiveness of MC_MEM. And in the following section, the current responses of different TL structures are discussed.

IV. RESPONSES OF DIFFERENT TRANSMISSION LINE STRUCTURES

In the field-to-transmission line coupling, the TL height h above RC metallic wall is a key parameter affecting the current response. In order to obtain the characteristics of TL responses with different h, some examples are calculated and shown in Fig.4 while other structural parameters are the same in Table Ⅰ.

As shown in Fig.4, the response characteristics with different h are similar with each other. Along with h increasing, the magnitude of the current responses become larger, while the increment becomes smaller. The lower h means the TL is closer to the wall, and the coupled power is fewer. This can be explained by the boundary and working volume field distribution inside a RC. When the $h \geq 0.75\text{m}$, the current responses are similar because the TL is located in the working volume where the EM fields are statistically uniform.

Then affect of other two position parameters x_0 and z_0 are shown in Fig.5 and Fig.6 while other structural parameters are the same in Table Ⅰ.

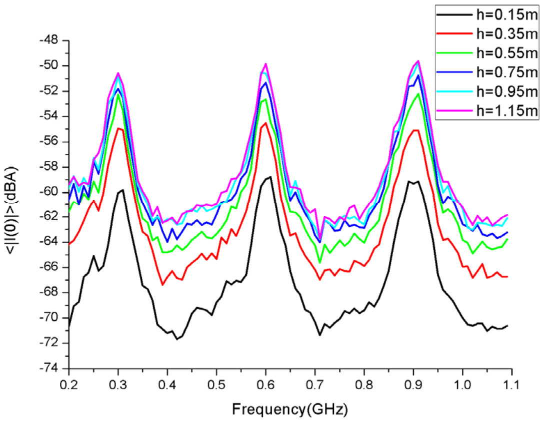

Fig. 4. Current responses of TL with different height h.

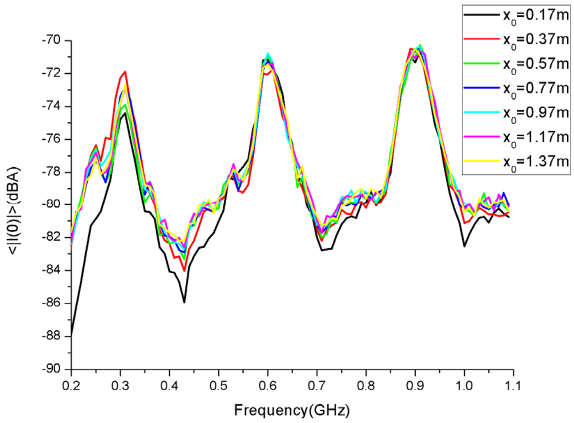

Fig. 5. Current responses of TL with different x_0.

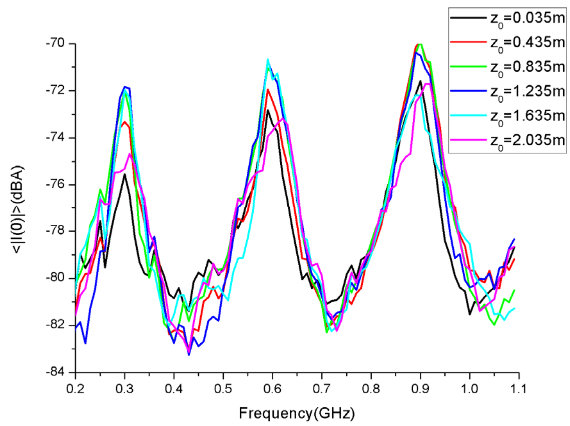

Fig. 6. Current response of TL with different z_0.

As shown in Fig.5 and Fig.6, the response characteristics and magnitudes of x_0 / z_0 are similar with each other. Because the positions of these TLs are all in the boundary area, so there is no obvious separations shown in Fig.4. By comparing current responses of different TL structures corresponding to h, x_0 and z_0, it can be seen that MC_MEM can statistically describe EM field in both the working volume and the boundary area. Compared with PWI, MC_MEM has following advantages: 1) MC_MEM is based on mode theory of resonant cavity, the boundary condition information are included, so the statistical characteristics of the boundary field can be expressed more directly; and 2) due to the intrinsic position dependence, MC_MEM can provide continuous representation of the distance when the observation point moving continuously from a position far from the wall to another position near the wall.

V. Conclusion

In this paper, MC_MEM is adopted to construct EM field distribution inside a RC. The effectiveness of this method is verified by the current responses of TL located inside a RC which agrees with the results obtained by PWI method. In addition, current responses of different TL arrangement are discussed. Although field-to-transmission line coupling inside a RC is complicated due to randomness and uncertainty of EM field distribution, MC_MEM can be another alternative statistical model to describe EM field distribution inside a RC, and be used to statistically solve the EM field-to-transmission line coupling problems inside the RC to avoid immense computational cost and HFRS. In the future works some complicated structures such as multiconductor TLs, curved TLs will be further studied.

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