A Load Effect Evaluation of a Transmission Line Exciting Chamber

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***Abstract*— This paper presents a theoretical evaluation of the phase shifting excitation and load effects in a Transmission Line Excitation Chamber. It is suggested as an alternative for immunity tests because of the restrictions related to canonical chambers. Here, two methods are used to calculate the E-field: a semi-analytic approach and a numerical one. The semi-analytic method is based on the well-known modal expansion while a commercial software is used for numerical simulations. The results regarding the field profile and the related statistical indexes of merit are presented and used to evaluate the chamber performances.**

Keywords- reverberation chamber, transmission lines, random excitations and loads

I. INTRODUCTION

Canonical chambers - like Reverberation Chambers (RC) and TEM chambers - are generally used for electromagnetic immunity testing despite their particular operational restrictions. RCs using mechanical paddles or frequency stirring provide a statistical E-field uniformity in all the directions inside the working volume [1]. Nevertheless, the frequency operation of RCs is inversely proportional to the chamber dimensions and it is a constraint for low frequency tests. The International Standards recommend the RC configuration for immunity tests over 80 MHz frequencies [2]. On the contrary, TEM chambers operate in the low frequency range. Introducing a stripline inside the chamber, a deterministic E-field uniformity is reached over a working area parallel to the plate, but not for all the polarizations in the chamber volume. The performances can however be extended for all the polarizations using three orthogonal striplines [3]. Recently, an alternative concept called Transmission Line Excitated Chamber (TLEC) has been proposed, based on a phase shifting excitation of several transmission lines (TL). For the sake of illustration, a structure constituted of three conductors with a phase shifting excitation has been investigated in [4].

Basically, a chamber excited by several TLs presents several TEM modes inside the closed metallic cavity. The resulting standing waves depend on the position of the TLs, on the amplitude and phase of the excitations and on the loading at the end of the TLs. Those parameters are important in the search for a suitable chamber working volume; they can be modified electronically, resulting in a random standing wave profile. Based on this, the performances of the TLEC can be improved to satisfy the pre-defined uniformity criteria within a wide frequency range, even at frequencies lower than 80 MHz. In this work, we present semi-analytical and numerical approaches for evaluating the performance of a TLEC.

This work was partially supported by Capes-Cofecub (07/0568), FAPESP (2007/51192-6) and Brazilian Navy.

II. SEMI-ANALYTIC APPROACH

A. *Analytic expression for a TL*

Consider the TL geometry given by Fig.1. When one analyzes the E-field of the single TEM mode, the dependence with *z* longitudinal direction can be decoupled from the ones with the transverse *x* and *y* directions. Indeed, the propagation, which exists for any frequency, can be described by a function $e^{-jk_0 z}$ when an incident wave is considered; k_0 is the wave number in the vacuum. The problem of the impact of possible reflections at the end of the TL will be addressed further in section II.C.

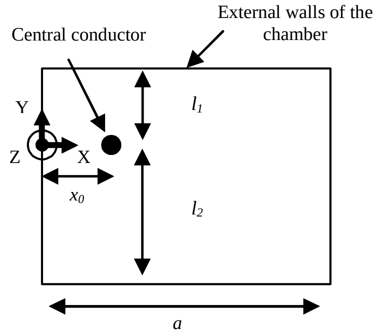


Figure 1. Geometry of a TL in the transverse plane

The E-field of a TEM mode in the transverse plane can be evaluated by the following analytical expressions:

$$E_{TEM\,X}(x,y)=\eta_0\sqrt{\frac{2}{a}}\sum_{m=1}^{+\infty}cos\left(\frac{m\pi}{a}x\right)\times\begin{cases}\alpha_{1m}sh\left(\frac{m\pi}{a}(y-l_1)\right) & y>0\\ \alpha_{2m}sh\left(\frac{m\pi}{a}(y+l_2)\right) & y<0\end{cases} \quad (1)$$

$$E_{TEM\,Y}(x,y)=\eta_0\sqrt{\frac{2}{a}}\sum_{m=1}^{+\infty}sin\left(\frac{m\pi}{a}x\right)\times\begin{cases}\alpha_{1m}ch\left(\frac{m\pi}{a}(y-l_1)\right) & y>0\\ \alpha_{2m}ch\left(\frac{m\pi}{a}(y+l_2)\right) & y<0\end{cases} \quad (2)$$

with

$$\alpha_{1m}=\frac{J_m\dfrac{th\left(\frac{m\pi}{a}l_2\right)}{ch\left(\frac{m\pi}{a}l_1\right)}}{th\left(\frac{m\pi}{a}l_1\right)+th\left(\frac{m\pi}{a}l_2\right)},\quad \alpha_{2m}=-\frac{J_m\dfrac{th\left(\frac{m\pi}{a}l_1\right)}{ch\left(\frac{m\pi}{a}l_2\right)}}{th\left(\frac{m\pi}{a}l_1\right)+th\left(\frac{m\pi}{a}l_2\right)} \quad (3)$$

where η_0 is the vacuum wave impedance and J_m the harmonic coefficients related to the current density on the central conductor. Assuming that the conductor is an infinitely thin wire along z axis, one finds:

$$J_m=I_0\sqrt{\frac{2}{a}}sin\left(\frac{m\pi}{a}x_0\right) \quad (4)$$

B. Several lines and Phase Shifting

When several TLs are ended with the same load, the E-field can still be written using the separation of variables in the transverse plane and in the longitudinal direction. The problem can then be treated by superposition:

$$\vec{E}_{TOT}(x,y)=\sum_i I_i\vec{E}_{i\,TEM}(x,y) \quad (5)$$

where $E_{i\;TEM}$ is the E-field due to the i^{th} TL for a current of amplitude 1 and I_i represents the applied excitation current. The phase shifting between the TLs has then an effect on the repartition of the E-field in the transverse plane.

C. Load Shifting

The load at the end of the TLs introduces a reflection coefficient Γ that affects the longitudinal repartition of the field:

$$\vec{E}(x,y,z)=\vec{E}_{TOT}(x,y)\times\left(e^{-jk_0z}+\Gamma e^{+jk_0z}\right) \quad (6)$$

Concerning the stripline used in canonical TEM chambers, the design of the TL is such that there is no reflection. Then the magnitude of the field is uniform in z direction. Using a TL with a thin wire, there is a discontinuity at the end of the line and it is difficult to match the line with the suitable load; then $|\Gamma|\neq 0$ and a stationary wave is expected.

However, the maximum of E-field can be moved changing the phase of Γ. Consider the worst case $|\Gamma|=1$. Suppose one can change the phase ϕ of $\Gamma=e^{j\phi}$; this can be achieved for example with a phase shifter ended by a short circuit. Then the complete E-field is given by:

$$\begin{aligned}\vec{E}(x,y,z)&=\vec{E}_{TOT}(x,y)\times\left(e^{-jk_0z}+e^{j\phi}e^{+jk_0z}\right)\\&=2\vec{E}_{TOT}(x,y)\times cos\left(k_0z+\frac{\phi}{2}\right)e^{j\phi/2}\end{aligned} \quad (7)$$

the phase shifting $\phi/2$ in the cosinus function shows that the maxima and minima of the E-field in z direction move with ϕ.

When the phase varies linearly between 0 and 2π, the mean effect can be calculated as follows:

$$\vec{E}_{average}(x,y,z)=\int_0^{2\pi}\left|\vec{E}(x,y,z)\right|\frac{1}{2\pi}d\phi=\frac{4}{\pi}\left|\vec{E}_{TOT}(x,y)\right| \quad (8)$$

the average E-field is no more dependent on z direction. Thus, it is possible to homogenize the field in z direction even if the TL is unmatched.

III. Numerical Approach

Numerical evaluation was performed with the Finite Integration Technique by using the commercial software CST-MWS ® [5]. The interest is that this approach is more realistic than the semi-analytic one since it takes into account the connection of the TLs outside the chamber; those details introduce discontinuities that can have an impact on the distribution of the E-field. A 3D TLEC model is built considering PEC walls and PEC TLs. The loads are set using ports defined at the end of the TLs while the phase shifting excitation is implemented by a post-processing approach.

A procedure applying Matlab® Activex commands was performed in order to set up the calculation parameters at CST-MWS® and to perform the indexes of merit calculation discussed in the following section.

IV. Indexes of Merit

The uniformity of the field is evaluated using the indexes of merit defined in [6]. Due to the phase and load shifting, the E-field considered at any point of the chamber is the average field $E_{average}$ in time. Considering a spatial point k in the chamber, one finds for the x polarization of the average field:

$$E^k_{average\_x}=\int_{[0,2\pi]^{M+1}}\frac{\left|E^k_x(\phi,\varphi_1,\ldots,\varphi_M)\right|}{(2\pi)^{M+1}}d\phi\prod_{i=1}^{M}d\varphi_i \quad (9)$$

with ϕ the phase of Γ, φ_i the phase of the current I_i in the i^{th} TL and M the number of TLs. Numerically, the integral is computed using a finite number of phases.

Then the mean field $\overline{E}_x$ and the standard deviation σ_x in the spatial domain can be computed from the average field given in (9):

$$\begin{aligned}\overline{E}_x&=\frac{1}{N}\sum_{k=1}^{N}E^k_{average\_x}\\ \sigma_x&=\sqrt{\frac{1}{N-1}\sum_{k=1}^{N}\left(E^k_{average\_x}-\overline{E}_x\right)^2}\end{aligned} \quad (10)$$

with N the number of points inside the chamber where the field is evaluated.

The normalized standard deviation in dB $\hat{\sigma}_x$ in x direction is defined by:

$$\hat{\sigma}_x=20\log_{10}\left(\frac{\overline{E}_x+\sigma_x}{\overline{E}_x}\right) \quad (11)$$

The indexes in y and z directions are calculated similarly.

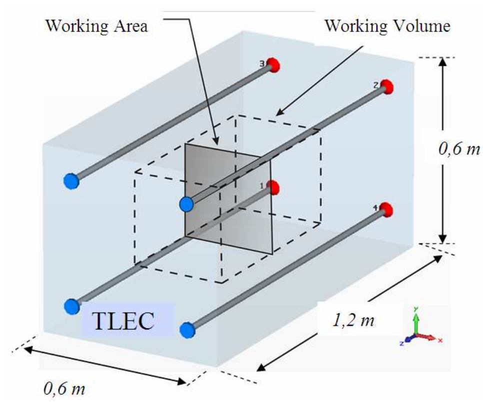


Figure 2. WV and WA definitions in the TLEC

V. APPLICATION AND RESULTS

A TLEC with dimensions of 0.6m×0.6m×1.2m (see Fig.2*)* has been considered; the volume under evaluation (WV) is a parallelepiped of dimensions 0.3m×0.3m×0.6m centered at the middle of the chamber. Besides that, the area under evaluation (WA) is a square of dimensions 0.3m x 0.3m at the center of WV. All the simulations are performed for a frequency of 80 MHz.

A. Semi-analytical results

The semi-analytical approach has been applied in the transverse plane *{x, y}* since the variation of E-field in z direction can be canceled using a suitable load shifting. The study concerns the influence of the phase shifting when several TLs are considered.

Fig.3 gives the E-field computed inside the TLEC when two kinds of TLs are considered: a TL with a thin wire conductor and a stripline with a plate conductor as it is used in canonical TEM chambers.

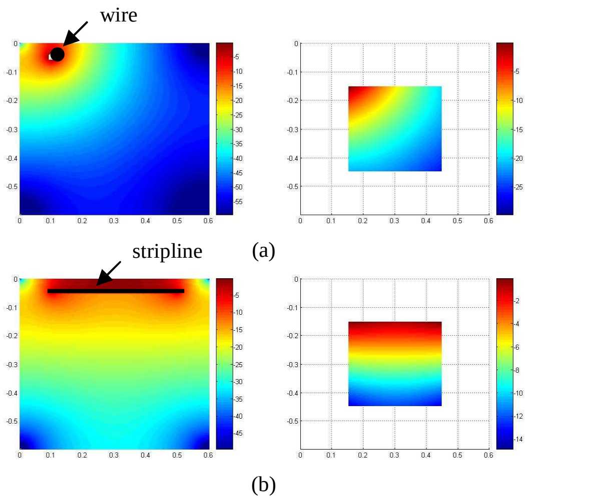


Figure 3. Distribution of the normalized E-field in the transverse plane inside the chamber (on the left) and inside the WA (on the right) in dB: (a) TL with a thin wire conductor (b) stripline used in canonical TEM chambers

It appears that none of the TL induces a uniform field; however the variation of the E-field magnitude inside the working area is greater in the case of the TL with a thin wire conductor (30 dB) compared to the stripline (15 dB). This result should prove that the stripline is a better candidate.

However when one takes into account some practical considerations in the realization of the lines, the TL with wire conductor remains an attractive solution. Then, to improve the E-field uniformity, a solution consists in using several TLs. Fig.4 illustrates when currents with $I_1=I_2=1$ and $I_3=I_4=-1$ flows along 4 TLs inside the TLEC; as one can see, it still remains minima and maxima of the E-field.

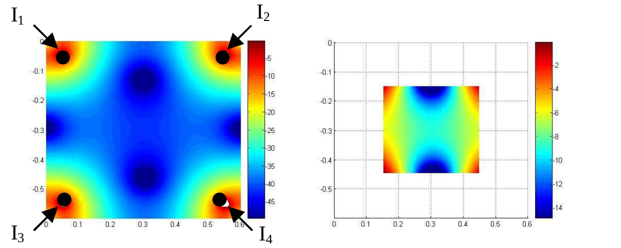


Figure 4. Distribution of the normalized E-field inside the chamber with 4TL excited by $I_1=I_2=1$ and $I_3=I_4=-1$

Basically, it is possible to move the minima and maxima of the total E-field inside the working area by changing the excitations I_1, I_2, I_3 and I_4 of the 4 TLs. For a sake of illustration, two examples are given Fig.5.

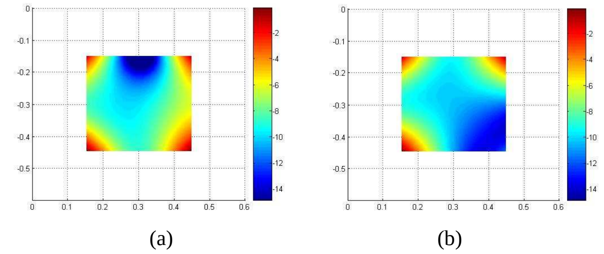


Figure 5. Distribution of the normalized E-field inside the working area for different excitations: (a) $I_1=I_2=1$ $I_3=j$ $I_4=-1$ (b) $I_1=1$ $I_2=j$ $I_3=-j$ $I_4=-1/4$

A better uniformity of the E-field can then be achieved by introducing a random variation of the excitations. The excitation shifting can be applied to the amplitude or to the phase of the different currents. Fig.5 shows that the effect on the average E-field is the same whenever the phase or the amplitude is supposed to be random. However, due to practical considerations, the phase shifting technique should be retained here. The variation of the E-field magnitude inside the working area is less important in the case of the 4 TLs with phase shifting (10 dB) compared to the stripline (15 dB) studied previously (see Fig.3b).

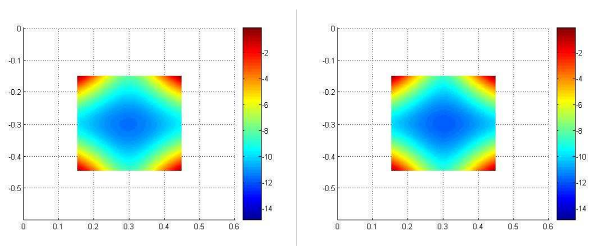


Figure 6. Distribution of the mean normalized E-field inside the working area with an amplitude shifting (on the left) or a phase shifting (on the right)

Results in terms of indexes of merit are reported in Table I. It appears that the number of TLs is an important parameter: the standard deviation decreases of 3 dB when 4 TLs are introduced instead of 2 TLs. Moreover, the phase shifting improves of 0.5 dB to 3 dB the performances of the chamber.

TABLE I. STANDARD DEVIATIONS FOR SEMI-ANALYTICAL APPROACH

Chamber Configuration		Standard Deviation (dB)		
Number of TL	Phase shifting	$\hat{\sigma}_x$	$\hat{\sigma}_y$	$\hat{\sigma}_{x,y}$
1	-------	5.7	6.0	5.9
2	No	6.5	3.3	5.3
2	Yes Random	5.2	4.3	4.8
4	No	6.4	2.0	5.0
4	Yes Random	3.3	3.3	3.4
TEM Chamber	-------	5.1	3.1	4.6

B. Numerical results

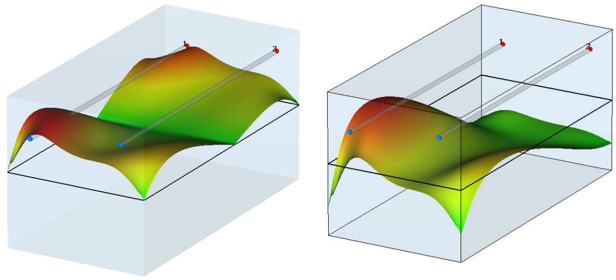
Table II presents the indexes of merit calculated using CST MWS ® software when the TLs are terminated by a 50 Ω load (the characteristic impedance of the TLs is 250 Ω). As one can see, the results in the WA are closed to the ones given in table I: for example the difference is about 0.5 dB in the case of 4 TLs with random phase shifting. However, there is a difference with the results when the WV is considered: this is due to the standing wave that appears because the TLs are unmatched. However, the difference never exceeds 1 dB because the dimension of the WV in *z* direction (0.6 m) is not large compared to the wavelength (3.75 m at 80 MHz).

TABLE II. STANDARD DEVIATIONS FOR NUMERICAL APPROACH (LOAD 50Ω)

Chamber Configuration			Standard Deviation (dB)		
Number of TL	Phase shifting	Working region	$\hat{\sigma}_x$	$\hat{\sigma}_y$	$\hat{\sigma}_{x,y}$
1	----	WA	6.1	6.1	6.1
		WV	7.3	7.3	7.3
2	No	WA	7.7	3.6	4.9
		WV	7.8	3.8	5.1
2	Yes Random	WA	5.9	4.0	4.8
		WV	6.0	4.2	5.0
4	No	WA	6.5	2.7	3.8
		WV	6.6	2.9	4.0
4	Yes Random	WA	3.9	3.9	3.9
		WV	4.0	4.1	4.1

The performances in the WV can be improved by a load shifting. The effect of changing the load is presented in Fig.7.

It appears that the maximum of E-field moves between a load of -j500 Ω and +j500 Ω. Considering that the characteric impedance of the TLs is 250 Ω, one finds that the reflection coefficient Γ is respectively $e^{-j0.93}$ and $e^{+j0.93}$; going back to equation (7), one expects that the minimum of E-field moves of $0.93 \div k_0 = 0.55$ m between both loads. This result is illustrated by the simulations reported Fig.7 (remind that the dimension of the chamber in *z* direction is 1.2 m, that is to say approximatively 2×0.55 m).



(a) (b)

Figure 7. . Distribution of the E-field modulus inside the chamber for differents loads (a) -j500 Ω load (b) +j500 Ω load

Table III presents the indexes of merit calculated when the load shifting is applied to the TLs.

TABLE III. STANDARD DEVIATIONS FOR NUMERICAL APPROACH (LOAD SHIFTING)

Chamber Configuration			Standard Deviation (dB)		
Number of TL	Load and Phase shifting	Working region	$\hat{\sigma}_x$	$\hat{\sigma}_y$	$\hat{\sigma}_{x,y}$
1	Yes, random	WA	6.1	6.0	6.0
		WV	6.2	6.2	6.2
2	Yes, random	WA	5.5	4.0	4.8
		WV	5.7	4.2	4.4
4	Yes, random	WA	3.5	3.4	3.5
		WV	3.7	3.7	3.7

As one can see, the performances of the TLEC is sligthly improved compared to the results obtained without the load shifting. Moreover, the results between WA and WV are very close: for example the difference is 0.1 to 0.2 dB in the case of a single TL.

CONCLUSION

It has been shown that a random profile of the standing waves in a TLEC can be obtained by an appropriate phase and load shifting of the TLs, which can be performed electronically. Then, when a TLEC is well designed and operated, it can reach and overcome the uniformity standards stated to canonical chambers.

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