Design and Analysis of Transmission Line System for Electromagnetic Immunity Test on Motorcycles

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Abstract — This research will first utilize Maxwell’s equations and the fundamental transmission line theory to analyze the electromagnetic field distribution generated by the EMS test facility, Transmission Line System (TLS) and to estimate the high-order electromagnetic modes induced by EUT inside various metallic structure of TLS under the operating frequency band of 100kHz-20MHz. Afterwards we design and simulate the system by means of the numerical analytical software, HFSS, which is based on the Finite Element Method. Finally we’ll use the simulated data and take practical effects that may occur into account to improve the TLS architecture for the optimal performance.

Keywords — EMC, EMS, Equipment Under Test (EUT), Finite Element Method (FEM), Numerical Analysis, Transmission Line System (TLS).

I. INTRODUCTION

In recent years, due to the rapid advance of technology, the application of mobile multi-media has encroached on the vehicle industry. Various kinds of mobile communication linking equipment are gradually used in vehicles. To avoid the mutual electromagnetic interference among these electronic apparatuses, the international organizations begin to institute the standards aimed at information, electronic products and associated with EMC, such as ISO, CISPR and so forth.

EMC design has become a vehicle manufacture’s subject urgently to solve and guard against. The EMC laboratory located in Automotive Research & Testing Center (abbrev. ARTC) has finished the establishment of EMS tests for full vehicles, which uses the log-periodic array antenna as the field-generating device. But at lower frequency band requested in ISO 11451 test standards (100kHz-20MHz), the antenna size will be too large to be utilized in the present facilities according to the antenna theory. And operating at low frequency, the radiation efficiency is so low that the huge output power will be excessively wasted. To avoid the above defects, the TLS was designed according to ISO 11451-2 in this research.

II. TRANSMISSION LINE ANALYSIS

Traditionally, the transmission line is represented as two parallel, equal-length conducting wires, the reason is that the transmission line capable to transmit TEM waves must have at least two conductors. Under the transmission line effect, one section of conducting metal wire must take the corresponding relations of its interior resistance, conductance, susceptance, and reactance into account. In this research, we take the self-designed metal structure as one conducting wire and take the ground plane of semi-anechoic chamber in ARTC as the second conducting wire which is treated as a fixed earth plane. And we also take air as the medium parameter within the two conductors.

We will go on to find the mathematical representation of the electromagnetic fields excited by TLS utilizing the fundamental transmission line theory. In the TEM case, the electric field, \( E(d) \), is related with the distance of two conducting wires, measurement point and the voltage distribution, as shown in equation (1).

\[
E(d) = -\frac{V(d)}{h} \tag{1}
\]

where \( h \): the height from upper conducting wire to ground plane.

To calculate \( V(d) \), we have to firstly obtain the initial voltage distribution and analyze the system by using the equivalent circuit model, as shown in Fig. 1.

\[
V(0) = V_s \frac{Z_{in}}{Z_v + Z_{in}} \tag{2}
\]

where \( Z_{in} \) can be calculated by utilizing the following formula:

\[
Z_{in} = Z_0 \frac{Z_L + jZ_0 \tan \beta l}{Z_0 + jZ_L \tan \beta l} \tag{3}
\]

where \( l \) : the length of the transmission line

\( Z_0 \): characteristic impedance of TLS
**Z L**: load impedance of TLS

\[ \beta = \frac{2\pi}{\lambda} \] : phase constant

\[ V(d) \] is the voltage distribution generated by the incident waves and reflected waves of initial voltage, \( \bar{V}(0) \), at \( d = 1 \):

\[ V(d) = \bar{V}(0)e^{-j\beta l}(e^{j\beta d} + \Gamma_x e^{-j\beta d}) \] (4)

where \( \Gamma_x \) : the voltage reflection ratio at the load of TLS

\[ \Gamma_x = \frac{Z_L + Z_0}{Z_L - Z_0} = \Gamma_x e^{j\phi_x} \] (5)

From equation (4):

\[ \bar{V}(0) = \frac{V(0)}{1 + \Gamma_x e^{-2j\beta l}} \] (6)

Combining equations (1),(2) and (4), we can obtain the electric field excited by TLS, as shown in equation (7).

\[ E(d) = \frac{-V_x Z_0 e^{j\beta l} + \Gamma_x e^{-j\beta l}}{h(Z_L + G) e^{j\beta l} + \Gamma_x e^{-j\beta l}} \] (7)

III. ELECTROMAGNETIC MODES INDUCED BY EUT IN TLS

For a transmission line with arbitrary cross-sections parallel to z-axis, its wave modes will be determined by the metal boundary of cross-sections. Suppose that the entire structure of TLS is uniform on its cross-sections and extends infinitely along the z-axis and all metals are treated as ideal conductors. The following will discuss some special wave modes induced by EUT in TLS. [2]

A. TEM wave

TEM wave is defined as \( E_z = H_z = 0 \). When the transmission line is composed of two or more conductors, TEM wave can exist. Under EMS tests, it assumes that the plane waves have no contributions of electromagnetic field in the direction of propagation. Hence it is also a kind of TEM wave. The wave impedance of TEM wave is given by equation (8).

\[ Z_{TEM} = \frac{E_x}{H_y} = \frac{-E_y}{H_x} = \frac{\mu}{\beta} = \frac{\sqrt{\mu/\varepsilon}}{\beta} = \eta \] (8)

where the characteristic impedance which not only depends on the geometry but also the dielectric in the medium in the transmission line directly relates the voltage to the current on the transmission line.

B. TE wave

TE wave is defined as \( E_x = 0 \) and \( H_z \neq 0 \), and the wave impedance of TE wave is shown in equation (9).

\[ Z_{TE} = \frac{E_x}{H_y} = \frac{-E_y}{H_x} = \frac{\mu}{\beta} = \frac{k\eta}{\beta} \] (9)

where \( k = \omega \sqrt{\mu\varepsilon} = \frac{2\pi}{\lambda} \) is the wave number of the medium in the transmission line. In equation (9), we find that the wave impedance is a function of frequency. When it exists in TLS, the performance of the system will get worse, and this is a so-called high order mode.

C. TM wave

TM wave is defined as \( H_x = 0 \) and \( E_z \neq 0 \), and the wave impedance of TM wave is shown in equation (10).

\[ Z_{TM} = \frac{E_x}{H_y} = \frac{-E_y}{H_x} = \frac{\beta}{\omega\varepsilon} = \frac{\beta\eta}{k} \] (10)

where \( k = \omega \sqrt{\mu\varepsilon} = \frac{2\pi}{\lambda} \) is the wave number of the medium in the transmission line. In equation (10), we find that the wave impedance is a function of frequency. When it exists in TLS, the performance of the system will get worse as well, and this is a so-called high order mode.

IV. DESIGN AND SIMULATION OF TRANSMISSION LINE SYSTEM

In this research, the architecture of TLS is a type of parallel conducting plate. Suppose that the width of the system is \( w \) and the distance between two metal plates is \( d \). We can analyze it by using transmission line theory to find the associated parameters of equivalent circuit model and calculate the characteristic impedance of TLS.

For a transmission line with parallel conducting plate structure, its associated parameters of equivalent circuit model \((R, L, G, C)\) are given by equation (11).

\[ L = \frac{\mu d}{w} \]

\[ C = \frac{\varepsilon w}{d} \]

\[ R = \frac{2R_s}{w} \]

\[ G = \frac{\omega\varepsilon w}{d} \] (11)
where \( R_s = \frac{1}{\sigma \delta_s} \) is the surface resistance of metal conductors and \( \varepsilon', \varepsilon'' \) are the real part and the imaginary part of dielectric constant \( \varepsilon = \varepsilon' - j\varepsilon'' = \varepsilon'(1 - j \tan \delta) \), respectively. \( \tan \delta \) is the loss tangent.

The TLS under this research is aimed at the EMS tests for the frequency band of 100kHz-20MHz, so the electrical length of this system is relatively short. Because of the low loss of TLS, its characteristic impedance can be simplified as:

\[
Z_0 = \sqrt{\frac{L}{C}}
\]

(12)

Assume that the distance between two metal plates is \( d \) and the width of the plates is \( w \). The medium between two metal plates is air and the aluminum plates (thickness: 3mm) is taken as the metal material of TLS, so we can obtain the designing parameter as follows:

\[
L = \mu_0 d \quad C = \varepsilon_0 \frac{w}{d} \Rightarrow Z_0 = \sqrt{\frac{L}{C}} = 377 \times \frac{d}{w} \quad (\Omega)
\]

(13)

The terminal impedances of source and load of TLS are both 50Ω, so the dimensions of TLS have to follow the relation, as shown in equation (14).

\[
d \approx \frac{1}{7.54} \quad w
\]

(14)

With equation (11)–(14) and in accordance with the request on field generating device ISO 11451-2 and ECE/R10 stipulate [4], we can design a system whose mechanical architecture is as follows.

According to the mechanical architecture of TLS(Fig. 2.-Fig. 4.), we can simulate and analyze its characteristics using the simulating software, HFSS. The following are the simulated results of TLS.
V. CONCLUSION

From the previous analysis, we find that the performance of TLS with side-plates is better than that without side-plates (Fig. 7-Fig. 11). This is because the fringe effect is suppressed after the side-plates are installed on TLS. Due to this compensation, the excited field is more concentrated on the interior of TLS and greatly reduced to leak outside the test region.

Presently, TLS is still on metal processing, so we'll proceed with the calibration of field uniformity, the analysis of TLS testing in semi-anechoic chamber and the investigation of uncertainty in measurement after it is fabricated.

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