Cable Harness Modeling Using MTL Parameters Derived from Integral Equations

Muqi Ouyang
EMC Laboratory
Missouri University of Science and Technology
Rolla, MO, USA
ouyangm@mst.edu

Xu Wang
EMC Laboratory
Missouri University of Science and Technology
Rolla, MO, USA
xw7dh@mst.edu

Nevin Altunyurt
Ford Motor Company
Dearborn, MI, USA
naltunyu@ford.com

Varittha Sanphuang
Ford Motor Company
Dearborn, MI, USA
vsanphua@ford.com

Nitin Parsa
Ford Motor Company
Dearborn, MI, USA
nparsa@ford.com

Jun Fan
EMC Laboratory
Missouri University of Science and Technology
Rolla, MO, USA
jfan@mst.edu

***Abstract*— A method to calculate equivalent Multiconductor Transmission-Line (MTL) parameters through integral equations is proposed in this paper. In the mixed-potential integral equations (MPIE), the elements of harness part are converted to MTL parameters based on the relations between MTL parameters and partial elements of 1-D wire segments. Then, to include the effects of reference metal plane nearby, the equivalent MTL parameters can be derived from the MPIE equations with modified harness elements by keeping the solutions on harness part the same. The current distributions on wires calculated using the equivalent MTL parameters have good correlations with the results from the original MPIE solver, and the understanding on the behavior of cable harness routing over nonideal reference plane can be analyzed in more detail and accurately with the extracted equivalent MTL parameters.**

Keywords—cable harness, multiconductor transmission-line (MTL), integral equation

I. Introduction

In terms of full wave EM simulations, cable harnesses consisting of multiple wires are typically complicated geometries and require heavy computational resources to accurately model the harness [1]. In an attempt to cut down the computational effort, hybrid MTL solver has been developed. Hybrid MTL method was found to have good accuracy (within certain frequency range) when compared to full-wave EM simulations [2]. However when the MTL system is non-ideal, the accuracy deteriorates. On the other hand non-ideal MTL systems are more likely to generate larger radiations. Hence, there is a need to model the behavior of non-ideal MTL systems accurately and efficiently.

In the past, research has been done to improve the classic hybrid MTL method for fast and accurate modeling of nonideal MTL systems. In [3], an approximate method to simulate cable harness routing over a slotted plane is discussed by cascading the Z-parameters of the reference plane nearby into the MTL SPICE model. The ports of Z-parameters are located beneath the cable harness. After the cascading, the effects of the slot in the reference plane can be modeled with good accuracy. However, when the geometry becomes more complicated, it can be difficult to identify the proper locations of Z-parameters' ports on the plane. In [2], a multiple scattering method is proposed. Accurate solutions are achieved by several iterations between the harness domain and the plane domain. The multiple scattering method can achieve good accuracy on harness current calculation, but the iteration steps make this method less efficient. Also, the equivalent MTL parameters can't be obtained through the multiple scattering method because only voltage and current solutions on harnesses are modified during iteration steps, while the MTL parameters remain as original values during iterations.

In this paper, a method to calculate equivalent MTL parameters from integral equations is proposed. The methodology is introduced first, and the accuracy of proposed method is validated through the good correlation between results calculated using proposed method and the reference results in a nonideal MTL system. The derived equivalent MTL parameters can help analyze the behavior of MTL systems with nonideal reference plane nearby.

II. Theory

A. MTL Parameters Calculation for Ideal Transmission-Line Structure

Assume that length of the transmission line is L in $\hat{y}$ direction. The distance between the transmission line and the reference ground plane is h in $\hat{z}$. The number of wires is n. The infinite ground reference plane is located at $z = 0$.

The relation between the full-wave integral equations and the transmission-line per-unit-length parameters are derived in [4, 5]. From the Maxwell's equations, following equations on field-to-transmission line can be derived:

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$$\frac{\mathrm{d}V_i^s(y)}{\mathrm{d}y} + j\omega\frac{\mu}{4\pi}\sum_{j=1}^{n} I_j(y)\int_0^L g(y_i, y_j')\mathrm{d}y_j' = E_y^e(h_i, y) \quad (1)$$

$$\frac{\mathrm{d}}{\mathrm{d}y}\sum_{j=1}^{n} I_j(y)\int_0^L g(y_i, y_j')\mathrm{d}y_j' = -j\omega 4\pi\varepsilon V_i^s(y) \quad (2)$$

Where $g(y_i, y_j')$ is the half-space Green's function; k is the wave number; ω is the angular frequency; V^S and I are the voltage and current on wires; y and y' are the observation and source locations on wires; Subscript i and j indicate the index numbers corresponding wire segments. E_y^e is the external field excitation term at wire location.

Generally, the radius of wires, a, is much smaller comparing to h or L, and the shape of $|g(y, y')|$ is close to a pulse function when assuming the source locates at center of wires and the observation point is on the surface of wires.

Comparing (1) and (2) to the telegrapher's equations in frequency domain, the per-unit-length inductance L' and capacitance C' can be derived.

If the wire is divided into small segments and length of each wire segment is l_0, then the partial inductance $L_{P_{i,j}}$ and partial potential coefficient $P_{P_{i,j}}$ can be calculated through (3) and (4), respectively [5].

$$L_{p_{i,j}} = \frac{\mu}{4\pi}\int_{l_i}\int_{l_j} g(y, y')\mathrm{d}y'\mathrm{d}y \quad (3)$$

$$P_{p_{i,j}} = \frac{1}{4\pi\varepsilon}\frac{1}{l_i l_j}\int_{l_i}\int_{l_j} g(y, y')\mathrm{d}y'\mathrm{d}y \quad (4)$$

Where i and j are the index number of wire segments and $l_i = l_j = l_0$.

Thus, the equations to calculate MTL parameters for the k^{th} segment between wire i and wire j are:

$$L_{(TL)ik,jk} = \sum_y L_{ik,jy} \quad (5)$$

$$C_{(TL)ik,jk}^{-1} = P_{(TL)ik,jk} = \sum_y P_{ik,jy} \quad (6)$$

If $i = j$, $L_{(TL)ik,jk}$ and $C_{(TL)ik,jk}$ are the self-inductance and self-capacitance of wire i on the k^{th} segment. If $i \neq j$, $L_{(TL)ik,jk}$ and $C_{(TL)ik,jk}$ are the mutual-inductance and mutual-capacitance between wire i and wire j on the k^{th} segment. In addition, $L_{ik,jy}$ and $P_{ik,jy}$ are the partial inductance and partial potential coefficient between k^{th} segment on wire i and y^{th} segment on wire j.

B. MTL Parameters Calculation for Complex Structure

In the previous section, the method to calculate MTL parameters from integral equations is developed based on ideal situation: the reference ground plane is infinite and the plane has no discontinuity. However, in many practical applications, like the harness bundle routing in a vehicle, the reference plane is no longer flat and there can be many slots or gaps on the reference plane.

To calculate the MTL parameters when the geometry of reference structure is complex, the method can be elaborated in following steps:

Step 1: Discretize both wires and reference structure into small cells and solve the whole geometry using mixed-potential integral equations (MPIE). The final equation to solve the electric potential $\bar{\phi}$ and current $\bar{i}$ is (7) [7].

$$\begin{bmatrix} j\omega\bar{\bar{C}} & \bar{\bar{\Lambda}}^T \\ -\bar{\bar{\Lambda}} & j\omega\bar{\bar{L}} \end{bmatrix}\begin{bmatrix} \bar{\phi} \\ \bar{i} \end{bmatrix} = \begin{bmatrix} -\bar{I}^e \\ \bar{V}^e \end{bmatrix} \quad (7)$$

In (7), $\bar{\bar{C}}$ and $\bar{\bar{L}}$ are the distributed capacitance and inductance matrices, respectively; ω is the angular frequency and $\bar{\bar{\Lambda}}$ is the connectivity matrix. $\bar{I}^e$ and $\bar{V}^e$ are the external current and voltage excitation.

Step 2: In (7), partition the matrices $\bar{\bar{C}}$, $\bar{\bar{L}}$ and $\bar{\bar{\Lambda}}$ into the plane part (with subscript *PP*), harness part (with subscript *HH*)and coupling terms between plane and harness (with subscript *PH* and *HP*).

In the matrices $\bar{\bar{C}}_{HH}$ and $\bar{\bar{L}}_{HH}$, (5) and (6) are still valid for calculation of MTL parameters. Thus, the matrices of MTL parameters on the harness part, $\bar{\bar{C}}_{HH,TL}$ and $\bar{\bar{L}}_{HH,TL}$, can be obtained. Therefore, (7) can be written as:

$$\begin{bmatrix} j\omega\bar{\bar{C}}_{PP} & j\omega\bar{\bar{C}}_{PH} & \bar{\bar{\Lambda}}_{PP}^T & \bar{\bar{\Lambda}}_{HP}^T \\ j\omega\bar{\bar{C}}_{HP} & j\omega\bar{\bar{C}}_{HH,TL} & \bar{\bar{\Lambda}}_{PH}^T & \bar{\bar{\Lambda}}_{HH}^T \\ -\bar{\bar{\Lambda}}_{PP} & -\bar{\bar{\Lambda}}_{PH} & j\omega\bar{\bar{L}}_{PP} & j\omega\bar{\bar{L}}_{PH} \\ -\bar{\bar{\Lambda}}_{HP} & -\bar{\bar{\Lambda}}_{HH} & j\omega\bar{\bar{L}}_{HP} & j\omega\bar{\bar{L}}_{HH,TL} \end{bmatrix}\begin{bmatrix} \bar{\phi}_P \\ \bar{\phi}_H \\ \bar{i}_P \\ \bar{i}_H \end{bmatrix} = \begin{bmatrix} -\bar{I}_P^e \\ -\bar{I}_H^e \\ \bar{V}_P^e \\ \bar{V}_H^e \end{bmatrix} \quad (8)$$

Step 3: Calculate the equivalent MTL parameters $\bar{\bar{C}}_{MTL,EQ}$ and $\bar{\bar{L}}_{MTL,EQ}$ that satisfy (9). The solutions on the harness part are the goal and the effects from the nearby metal plane have been included in these equivalent matrices.

$$\begin{bmatrix} j\omega\bar{\bar{C}}_{MTL,EQ} & \bar{\bar{\Lambda}}_{MTL,EQ}^T \\ -\bar{\bar{\Lambda}}_{MTL,EQ} & j\omega\bar{\bar{L}}_{MTL,EQ} \end{bmatrix}\begin{bmatrix} \bar{\phi}_H \\ \bar{i}_H \end{bmatrix} = \begin{bmatrix} -\bar{I}_H^e \\ \bar{V}_H^e \end{bmatrix} \quad (9)$$

$\bar{\phi}_H$ and $\bar{i}_H$ in (9) should be the same as those in (8), so

$$\begin{aligned} \bar{\bar{C}}_{MTL,EQ} &= \left(\bar{\bar{C}}_{HH,TL} - \bar{\bar{C}}_{HP}\bar{\bar{C}}_{PP}^{-1}\bar{\bar{C}}_{PH}\right) + \\ &\left(\bar{\bar{\Lambda}}_{PH}^T - \bar{\bar{C}}_{HP}\bar{\bar{C}}_{PP}^{-1}\bar{\bar{\Lambda}}_{PP}^T\right)\left(-\omega^2\bar{\bar{L}}_{PP} + \bar{\bar{\Lambda}}_{PP}\bar{\bar{C}}_{PP}^{-1}\bar{\bar{\Lambda}}_{PP}^T\right)^{-1}\left(\bar{\bar{\Lambda}}_{PH} - \bar{\bar{\Lambda}}_{PP}\bar{\bar{C}}_{PP}^{-1}\bar{\bar{C}}_{PH}\right) \end{aligned} \quad (10)$$

$$\begin{aligned} \bar{\bar{L}}_{MTL,EQ} &= \left(\bar{\bar{L}}_{HH,TL} - \frac{1}{\omega^2}\bar{\bar{\Lambda}}_{HP}\bar{\bar{C}}_{PP}^{-1}\bar{\bar{\Lambda}}_{HP}^T\right) \\ &-\left(\bar{\bar{L}}_{HP} - \frac{1}{\omega^2}\bar{\bar{\Lambda}}_{HP}\bar{\bar{C}}_{PP}^{-1}\bar{\bar{\Lambda}}_{PP}^T\right)\left(\bar{\bar{L}}_{PP} - \frac{1}{\omega^2}\bar{\bar{\Lambda}}_{PP}\bar{\bar{C}}_{PP}^{-1}\bar{\bar{\Lambda}}_{PP}^T\right)^{-1}\left(\bar{\bar{L}}_{PH} - \frac{1}{\omega^2}\bar{\bar{\Lambda}}_{PP}\bar{\bar{C}}_{PP}^{-1}\bar{\bar{\Lambda}}_{HP}^T\right) \end{aligned} \quad (11)$$

$$\begin{aligned} \bar{\bar{\Lambda}}_{MTL,EQ} &= \left(\bar{\bar{\Lambda}}_{HH} - \bar{\bar{\Lambda}}_{HP}\bar{\bar{C}}_{PP}^{-1}\bar{\bar{C}}_{PH}\right) \\ &+\left(\bar{\bar{L}}_{HP} - \frac{1}{\omega^2}\bar{\bar{\Lambda}}_{HP}\bar{\bar{C}}_{PP}^{-1}\bar{\bar{\Lambda}}_{PP}^T\right)\left(\bar{\bar{L}}_{PP} - \frac{1}{\omega^2}\bar{\bar{\Lambda}}_{PP}\bar{\bar{C}}_{PP}^{-1}\bar{\bar{\Lambda}}_{PP}^T\right)^{-1}\left(\bar{\bar{\Lambda}}_{PP}\bar{\bar{C}}_{PP}^{-1}\bar{\bar{C}}_{PH} - \bar{\bar{\Lambda}}_{PH}\right) \end{aligned} \quad (12)$$

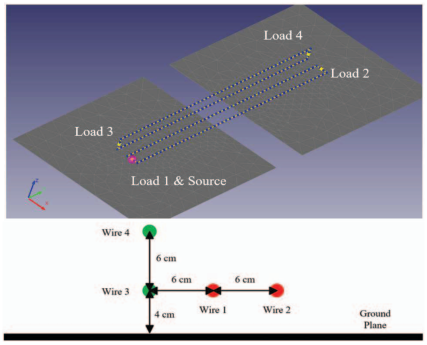


Fig. 1. Example of multiple wires routing over a gap in reference plane (a) overall model and (b) side view

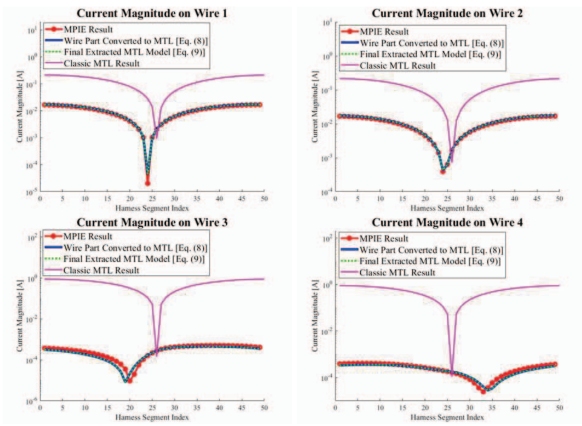


Fig. 2. Current distribution comparisons between different calculation methods at 100 MHz on Wire 1, 2, 3 and 4

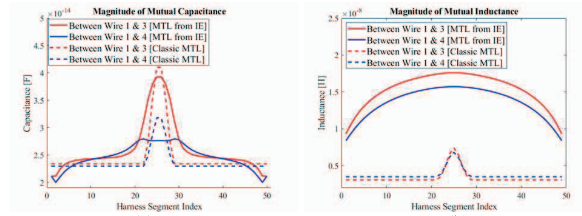
III. Numerical Validation

An MTL system with multiple signal wires and nearby reference plane is created to validate the accuracy of the extracted MTL parameters, as shown in Fig. 1. For this type of structure with discontinuity in reference plane, it can be challenging to solve the current distribution on wires accurately using the classic MTL method [1].

The length and radius of each wire is 1.5 m and 0.3 mm, respectively. All 4 loads are 0.1 Ohm resistive loads and the source is 1-V voltage source. There are 2 separate metal planes and the size in $\hat{x}$ and $\hat{y}$ directions of each plane is 0.8 m and 1 m, respectively, and the width of gap between them is 0.2 m.

The comparisons of current distributions along the wires using different calculation methods, MPIE, Wire Part Converted to MTL, Extracted MTL Model and classic MTL model, are shown in Fig. 2, and some of the extracted mutual MTL parameters are shown in Fig. 3. Only results comparisons at 100 MHz are shown here due to page limitations, and more results can be shown during the presentation.

The comparison results on current distribution along the wires show that the MTL model extracted from integral equations has good correlation with the original solution results, and the accuracy has large improvement compared to classic MTL results. The differences between the MTL parameters derived from integral equations and the parameters from classic



(a) (b)

Fig. 3. Comparisons between classic MTL parameters and extracted equivalent MTL from integral equations (IE) (a) mutual-capacitances and (b) mutual-inductances at 100 MHz

MTL method not only exist on wire segments routing over the discontinuity in reference plane, but also on wire segments over continuous reference plane. In addition, some parameters derived from integral equations have relatively larger differences comparing to classic MTL parameters, like the mutual inductances shown in Fig. 3(b). Identifying the factors contributing to these differences can help analyze MTL related problems.

IV. Conclusion

In this paper, a method to calculate equivalent MTL parameters from integral equations is proposed. The proposed method is validated with an MTL system consisting of multiple wires over a reference plane with discontinuity. Results showed that the errors of calculated current distributions along wires are much smaller comparing to classic MTL method.

With the extracted MTL parameters, a more detailed and accurate understanding on the behavior of MTL systems with nonideal reference can be obtained, and this can help analyze the radiation problems or crosstalk problems caused by wires routing on reference planes with discontinuities.

References

[1] Y. Wang, Y. S. Cao, D. Liu, R. Kautz, N. Altunyurt, and J. Fan, "Applying the multiple scattering (MS) method to evaluate the current response on a cable harness due to an incident plane wave," in *2018 IEEE International Conference on Computational Electromagnetics (ICCEM)*, 2018, pp. 1-3: IEEE.

[2] Y. Wang, Y. S. Cao, D. Liu, R. W. Kautz, N. Altunyurt, and J. Fan, "A Generalized Multiple-Scattering Method for Modeling a Cable Harness With Ground Connections to a Nearby Metal Surface," *IEEE Transactions on Electromagnetic Compatibility,* vol. 61, no. 1, pp. 261-270, 2018.

[3] D. Liu, "Common mode current estimation for cable bundle inside a vehicle," Ph.D. dissertation, Dept. Elect. Comput. Eng., Missouri Univ. Sci. Technol., Rolla, MO, USA, 2013.

[4] S. Tkatchenko, F. Rachidi, and M. Ianoz, "Electromagnetic field coupling to a line of finite length: Theory and fast iterative solutions in frequency and time domains," *IEEE Transactions on Electromagnetic Compatibility,* vol. 37, no. 4, pp. 509-518, 1995.

[5] A. E. Ruehli, "Equivalent circuit models for three-dimensional multiconductor systems," *IEEE Transactions on Microwave theory and techniques,* vol. 22, no. 3, pp. 216-221, 1974.

[6] S. Chabane, P. Besnier, and M. Klingler, "A modified enhanced transmission line theory applied to multiconductor transmission lines," *IEEE Transactions on Electromagnetic Compatibility,* vol. 59, no. 2, pp. 518-528, 2016.

[7] J. Fan, H. Shi, A. Orlandi, J. L. Knighten, and J. L. Drewniak, "Modeling DC power-bus structures with vertical discontinuities using a circuit extraction approach based on a mixed-potential integral equation," *IEEE Transactions on Advanced Packaging,* vol. 24, no. 2, pp. 143-157, 2001.