Experiments study of coupling parameters characterization of the multiconductor transmission lines

Yingjie Gan, Xiaoying Xu*
School of Sciences, Wuhan University of Technology, Wuhan, China
E-mail: xu_xiao_ying@126.com

Abstract. Although a number of papers have been published on the study of multiconductor transmission lines (MTLs) parameters characterization, little experiment studied on the MTLs, especially in the frequency domain. This paper presented a series of experiments of homogeneous MTLs, got the characteristic parameters such as the capacitance matrix and the inductance matrix, and analyzed the relationship between parameters and frequency. The correctness of the experimental results was verificated by the HFSS software simulation.

1. Introduction
With the requirement of high-speed, broadband, high density and miniaturization in the development of modern electronic technology, the distribution parameters of the transmission lines must be taken into account in power and communication system. In many cases coupling between lines can be attribute to the couple of MTLs [1].

The characteristic parameters determine the propagation of the MTLs and the terminal current and voltage. In most case, when the geometry length of the MTLs is less than 1/10 of the wavelength, the MTLs is considered to be the electrically small, and then the inductance is much lager than the capacitance [2]. Lumped parameters of the resistance and inductance are available to establish the equivalent circuit to analyze and calculate the MTLs coupling response.

One of the major ways, which MTLs electromagnetic interference (EMI) is coupling between lines, is that the degree of coupling can quantitatively characterize the strength of this coupling, using the scattering parameters (S-parameters) to determine the value of it.

This paper made measurements and calculations to the characteristic parameter matrices-scattering matrix ([S]), impedance matrix ([Z]) and the inductance matrix ([L]) of the MTLs. The measurements may generate error due to instrument or other reasons; thus, to verify the validity of the experiment, the measurements are compared with the HFSS simulation results. Mastering the law of the coupling parameters change with the frequency can provide a theoretical basis for the analysis of MTLs coupling and it also can guide engineering application.

2. Experimental tests
2.1 Experimental Principle
It is very convenient to use a network analyzer for measuring the S-parameter of transmission line

* To whom any correspondence should be addressed.
system. When it comes to the analysis and calculation, \([S]\) often needs to be converted to \([Z]\). At the reference surface of the network port, scattering matrix describes the relationship between the normalized incident wave and reflected wave, and \([Z]\) describes the relationship between the voltage and the current which are not normalized. Since \([S]\) and \([Z]\) describe the same network, there must be a transformational relationship [3].

The relationship between the network parameter \(Z_{ij}\) and \(S_{ij}\) is shown in Equation 1.

\[
Z_{11} = Z_c \frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}
\]

\[
Z_{12} = Z_c \frac{2S_{12}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}
\]

\[
Z_{21} = Z_e \frac{2S_{21}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}
\]

\[
Z_{22} = Z_e \frac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}
\]

The measurements of the characteristic parameters of MTLs commonly used transmission line terminal short-circuit and open-circuit impedance tests [4]. When the far end shorted and all the near ends but the driven line opened, by measuring current and voltage values of the near end, we can get the transmission lines impedance matrix:

\[
[Z_{sc}(s)] = [R_g] + s[L_g] \quad (s = j\omega)
\]

Then the relationship between the impedance matrix and inductance matrix became as follows:

\[
[Z_{Nonsc}(s)] = j\omega[L_{nm}]
\]

Open experimental measurement is the inductance matrix.

2.2 Experimental setup and testing

![Figure 1. Transmission lines parameter measurement experiment setup.](image)

The experimental device to measure the MTLs S-parameter was shown in figure1. The conductor lines were BV1 type single core copper cable and two conductors arranged in parallel with the same length.
Two small aluminum plate at both ends of the conductor wire screw up the lines, which were welded to the large ground plate to provide a low-impedance current path in the short-circuit measurement. The large ground plate is an aluminum plate, size of 1.5m×2m, which is connected to the ground line of network analyzer by wires [5].

Two transmission lines far ends shorted, after calibrated the network analyzer, probes connected to the near end, sweeping the S-parameter varying with frequency.

The network analyzer is a precise measuring instrument, so it is important to pay particular attention to the impact of its probe on the measurement results. In order to reduce measurement error, it should try to shorten the line length of the probe and ensure the probe fixture contact well with the transmission lines. In the process of measurement, be careful to stay away from the bench to reduce the interference on the measurement of human body electrostatic.

3. The HFSS simulation

Ansoft HFSS software is based on the finite element method. It is a 3D frequency-domain electromagnetic field calculation software, through the calculation of the electromagnetic field components of the grid cells to obtain the various physical quantities and parameters.

HFSS was used to model the experimental setup, which was shown in figure 2. The sizes of all components in the model were the same with the experimental measurement sizes.

![Figure 2. The HFSS model.](image)

To meet the requirements of electrically small, the calculation frequency limits from 1 MHz to 15 MHz, sampling step length is 1 MHz with lumped pot incentives [6]. The software simulation analysis can directly read the S-parameter and Z-parameter matrix data and the sampling frequency points.

4. Data analysis

4.1 S-parameter analysis

Part of the S-parameter data is shown in table 1.

Because the size and placement of the two transmission lines are the same, the scattering matrix is a reciprocal matrix, i.e. $S_{ij}=S_{ji}$. Table 1 gives the values of $S_{11}$ and $S_{12}$ parameters.

In table 1, the measurement and simulation data of S-parameter is slightly different, which is mainly due to the impact of probe fixture on the measure system. The experimental measurement of $S_{11}$ and $S_{12}$ parameters curve are shown in figure 3.

In figure 3, with increasing of frequency, $S_{11}$ continuously reduces, while $S_{21}$ rises, two curves level off after 10 MHz. From 1 MHz to 10 MHz, return loss decrease, while insertion loss increase, the MTLs reflection continuously goes down, meaning the ability of the system to transfer more energy.
Table 1. S-parameters comparison.

| f (MHz) | $S_{11}$ (dB) (expt) | $S_{12}$ (dB) (expt) | $S_{11}$ (dB) (sim) | $S_{12}$ (dB) (sim) |
|---------|----------------------|----------------------|---------------------|---------------------|
| 1       | -0.22                | -13.8                | -0.22               | -13.5               |
| 3       | -1.36                | -5.89                | -1.37               | -5.84               |
| 5       | -2.61                | -3.56                | -2.8                | -3.74               |
| 7       | -3.5                 | -2.67                | -3.43               | -2.72               |
| 9       | -3.98                | -2.31                | -3.86               | -2.4                |
| 11      | -4.17                | -2.19                | -3.99               | -2.31               |
| 13      | -4.16                | -2.2                 | -3.94               | -2.35               |
| 15      | -4.02                | -2.29                | -3.77               | -2.47               |

When the port is matched and the transmission line circuit has no load, the coupling between the transmission lines can be defined as follows:

$$C = 10\log(|S_{12}|)$$  \hspace{1cm} (4)

The bigger the value of $C$, the stronger the coupling between lines, and the greater the mutual interference. The curve that $C$ changes with frequency is shown in figure 4.

![Figure 3. The curve of S-parameters varies with frequency.](image)

![Figure 4. MTLs coupling degree.](image)

From the figure, we can see that with frequency increasing, the degree of coupling reduced, and the transmission performance of the transmission lines became better.

4.2 $L$-parameter analysis

Table 2. L-parameters comparison.

| f (MHz) | $L_{11}$ ($\mu H/m$) (expt) | $L_{12}$ ($\mu H/m$) (expt) | $L_{11}$ ($\mu H/m$) (sim) | $L_{12}$ ($\mu H/m$) (sim) |
|---------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 1       | 1.145                       | 0.071                       | 0.131                       | 0.036                       |
| 3       | 6.296                       | 0.366                       | 8.228                       | 0.158                       |
| 5       | 13.797                      | 0.781                       | 15.677                      | 0.312                       |
| 7       | 23.249                      | 1.269                       | 26.096                      | 0.460                       |
| 9       | 34.524                      | 1.970                       | 32.411                      | 0.763                       |
| 11      | 47.877                      | 3.222                       | 46.892                      | 1.558                       |
| 13      | 63.418                      | 4.484                       | 63.554                      | 2.593                       |
| 15      | 79.423                      | 4.466                       | 78.071                      | 1.608                       |
The measurement S-parameter matrix and simulation Z-parameter matrix can be converted to L-parameter matrix by (1) and (3). Part of the inductance matrix parameter data was shown in table 2.

The comparison of L_{11} parameter curves was shown in figure 5. L_1 was the simulation curve and L_2 was the experiment data. Figure 6 was about the contrast of L_{12} parameter curves. L_1 was the simulation curve and L_2 was the experiment curve.

\[ y = 1.129x^{1.564} \]  

(5)

As it can be seen in figure 5, the experimental and simulation self-inductance of MTLs is basically consistent with the simulation result, so the experimental one is valuable. Using Allometroc1 to fit a curve to the data, the fitted result and the curve in figure 4 mainly overlapped. The fitting formula is:

From (5), we can see that in the measured frequency range, the self inductance of MTLs is exponential growth with the frequency increase.

From the figure 6, we can see that the mutual inductance parameter data of experiments and simulation are quite different, but the trend of the curves are the same, so we can still analyze the relationship between mutual inductance and frequency from the figure. The difference mainly results from the biased error which is caused by the mismatch calibration of network analyzer and load in the measurements. Only if the correction is accurate and the load had total matched, the S-parameter is exact.

The mutual inductance of MTLs increases with frequency in the range of 1 to 13 MHz, thereafter, when the frequency increases, L_{12} decreases. It means that the mutual inductance self-resonant frequency is around 13 MHz. When frequency is below the self-resonant frequency, mutual inductance of MTLs increases with it; at the self-resonant frequency point, inductance reaches its maximum; when frequency over the point, the inductance decreases.

Figure 5 and 6 show that the inductive reactance of transmission lines is not constant while losses exist. Frequency mainly impacts the inductive reactance by the skin effect and proximity effect and this impact grows with the increase of frequency. While the frequency increases, the current through the cross section of transmission lines becomes uneven and moves to the periphery of conductors.

5. Conclusion
This paper introduced a method of measuring and calculating MTLs coupling parameters. When the far ends of MTLs shorted, it is possible to measure S-parameter matrix with analyzer network and then to convert out the L-parameter matrix. This method can help us to analyze the law of the variation of
coupling parameters with frequency. What’s more, it is convenient and suitable in the laboratory.

When the transmission lines cannot be seen as electrically small, we can still use S parameters to calculate the L-parameter matrices by formulas, so this method is suitable for the whole frequency band.

References
[1] Antonini G and Camillis L D 2009 Microw. Wirel. 19 65
[2] Paul C R 2008 Analysis of multiconductor transmission lines (USA: John Wiley & Sons)
[3] Chen X and Kildal P 2011 Proc. Int. Conf. On AP-S/URSI (Spokane) (New York: Institute of Electrical and Electronics Engineers) p1885
[4] Paul C R 2007 IEEE Trans. Electromagn. Compat. 49 237
[5] Rana M and Islam R 2011 Proc. Int. Conf. On ASEMDF (Sydney) (Chengdu: University of Electronic Science and Technology of China Press) p220
[6] Ryan C G M and Eleftheriades G V 2012 IET Microwaves Antennas Propag. 6 70