Analysis on Crosstalk for Coplanar Irregular-placed Cables Based on Cascading Method and Cubic Spline Interpolation Algorithm

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***Abstract* ─** The research on cable crosstalk is an important part of electromagnetic compatibility. The conventional research on cable crosstalk is mostly for parallel cables. However, most of the actual transmission line models are in a non-parallel state. A new method for the crosstalk prediction of coplanar irregular-placed cables is proposed in this paper. The method derives the integral form of the transmission line equation based on the cascade method. Combined with the cubic spline interpolation method for the processing of the per unit length parameter matrix, the crosstalk of the coplanar irregular-placed cables is predicted. The orthogonal experiment method is used to find that the distance between transmission lines has the greatest influence on crosstalk, followed by height from the current return plane, frequency, load and length. In order to verify the accuracy of the new method for crosstalk, the full wave method is introduced as a comparison method, and the experiment is introduced as a reference method. The verification results show that the new method has higher accuracy for the crosstalk prediction of coplanar irregular-placed cables, especially in the frequency band less than 100MHz.

***Index Terms* ─** Cascade method, crosstalk, cubic spline interpolation method, multi-conductor transmission line (MTL), orthogonal experiment method.

I. INTRODUCTION

In modern electronic systems such as drones, ships and vehicles, the narrowness of the installation space and the high speed of the signal lead to the increasingly serious damage to signal integrity caused by crosstalk [1]. Therefore, crosstalk suppression of cables is a non-negligible component of electromagnetic compatibility (EMC) [2]. It is of great theoretical and engineering significance for efficient operation of electrical equipment to explore the generation and transmission mechanism of cable electromagnetic crosstalk, and to predict the crosstalk of the transmission lines [3].

At present, the academic research on cable crosstalk is mainly based on the coupling of parallel cables. As early as the 1960s, the coupling formula and the famous BLT (Baum-Liu-Tesche) equations of three conductors under different port conditions were proposed [4]. The analysis methods of the structure of multi-conductor transmission line (MTL) mainly include full-wave method and transverse electromagnetic (TEM) field method [5]. In the crosstalk prediction of cables, it is further divided into prediction in the time domain and the frequency domain. Prediction in the time domain includes finite difference time domain (FDTD) method, time domain BLT equation method, cascade method [6-8], and prediction in the frequency domain mainly includes the moment of method (MOM) [9], modulus decoupling method [10].

Actually, the type of transmission line also includes coaxial cable [11], twisted pair cable [12], non-uniform cable and bundle cable [13-15]. Engineering applications are divided into optical fiber [16], aviation cable metal wire [17], vehicle cable [18]. The parameter matrix extraction method of the MTL includes theoretical calculation method and experimental method. The theoretical calculation method includes analytical method and numerical method [10]. The experimental method includes the scattering parameter method [19] and the separation network method [20].

However, most of the actual MTL models are in

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an irregular state. Coplanar irregular-placed cables are difficult to analyze through the conventional method. Artificial intelligence algorithm prediction is often used now, like the BP neural network algorithm [21-22]. The neural network algorithm requires a large number of data samples of crosstalk experiments measured at different frequencies. It is unrealistic to measure the crosstalk of connected and used cables in most cases. It is highly probable that the original spatial relative position of the cable will change during the experiment, causing the crosstalk characteristics to change again.

The previous research did not make detailed theoretical derivation and calculation of coplanar irregular-placed cables crosstalk. Therefore, the method of crosstalk prediction for coplanar irregular-placed cables still needs further research.

The rest of the paper is presented as follows. In Section II, the model of coplanar irregular cables is studied based on the theory of cascaded transmission line, and the theoretical integral calculation formula of the crosstalk is derived. In Section III, the elements of the inductance parameter matrix are calculated by the analytic method and the elements of the capacitance parameter matrix are solved by the finite element method (FEM) combined with the cubic spline interpolation method. And the orthogonal experiment method is used to compare and analyze the factors affecting the crosstalk of transmission lines. In Section IV, a specific coplanar irregular-placed cables model is analyzed by using the new method, full wave method, and the experimental method. The conclusions of this paper are given in Section V.

II. CROSSTALK SOLUTION OF COPLANAR IRREGULAR-PLACED CABLES MODEL

A. Regular-placed cable model

The regular-placed cable model in this paper refers to the parallel MTL model. The per unit length (p.u.l.) equivalent circuit of the parallel MTL is shown in Fig. 1, where dz is expressed as an infinitely short transmission line. The entries l_{ii} and l_{jj} represent the p.u.l. self-inductances, the entries l_{ij} and l_{ji} represent the p.u.l. mutual inductances. The entries r_{ii} and r_{jj} represent the p.u.l. resistances. The entries c_{ii} and c_{jj} stand for the p.u.l. self-capacitances, the entries c_{ij} and c_{ji} stand for the p.u.l. mutual capacitances. The entries g_{ij} and g_{ji} denote the p.u.l. conductances. The coupling effect of the MTL can be fully characterized by the model with high precision.

The matrix differential equation of the MTL is [10]:

$$\begin{cases} \mathrm{d}\overline{\boldsymbol{U}}(z)/\mathrm{d}z = -\boldsymbol{Z}\,\overline{\boldsymbol{I}}(z) \\ \mathrm{d}\overline{\boldsymbol{I}}(z)/\mathrm{d}z = -\boldsymbol{Y}\,\overline{\boldsymbol{U}}(z) \end{cases}, \tag{1}$$

$$\begin{cases} \boldsymbol{Z} = \boldsymbol{R} + \mathrm{j}\omega \boldsymbol{L} \\ \boldsymbol{Y} = \boldsymbol{G} + \mathrm{j}\omega \boldsymbol{C} \end{cases}, \tag{2}$$

where $\overline{\boldsymbol{U}}(\mathrm{z})$ and $\overline{\boldsymbol{I}}(\mathrm{z})$ are the voltage and current on the MTL, respectively. The p.u.l. impedance and the p.u.l. admittance matrix are represented by $\boldsymbol{Z}$ and $\boldsymbol{Y}$, respectively. The impedance matrix $\boldsymbol{Z}$ is composed of the p.u.l. resistance matrix $\boldsymbol{R}$ and the p.u.l. inductance matrix $\boldsymbol{L}$. The admittance matrix $\boldsymbol{Y}$ is composed of the p.u.l. conductance matrix $\boldsymbol{G}$ and the p.u.l. capacitance matrix $\boldsymbol{C}$. The p.u.l. parameter matrix $\boldsymbol{R}$, $\boldsymbol{L}$, $\boldsymbol{C}$ and $\boldsymbol{G}$ are symmetric matrices.

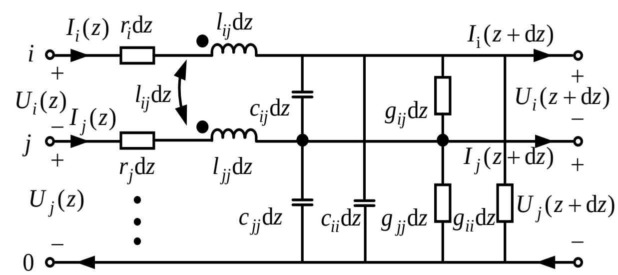

Fig. 1. Single spiral model.

B. Coplanar irregular-placed cables model based on the theory of cascade transmission line

For the purposes of research, the coplanar irregular placed cables model must satisfy the situation of no twisting or crossing between the wires. Cable differentiated into m segments is shown in Fig. 2. When m is large enough, the transmission lines between each segment are considered to be parallel, and each segment of the cable meets the parallel MTL theory.

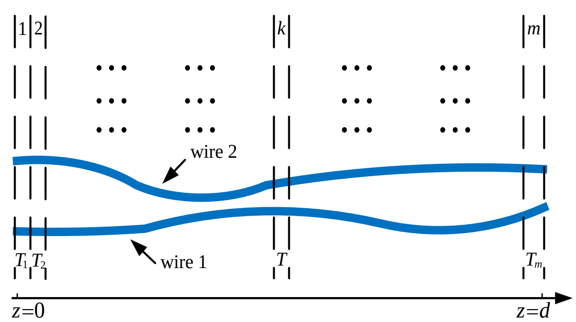

Fig. 2. The differential model of coplanar irregular-placed cables.

Similar to a regular-placed cable, each segment of the coplanar irregular-placed cables has a corresponding coupling matrix formula, and each segment has a parameter matrix $\boldsymbol{Z}$, $\boldsymbol{Y}$. For the k-th segment, the equation is:

$$\begin{cases} d\vec{U}(k)/dz = -Z_k \vec{I}(k) \\ d\vec{I}(k)/dz = -Y_k \vec{I}(k) \end{cases}, \tag{3}$$

where $\bar{\boldsymbol{U}}(\mathrm{k})$ and $\bar{\boldsymbol{I}}(\mathrm{k})$ are the voltage and current on the k-th segment. $\boldsymbol{Z}_k$ and $\boldsymbol{Y}_k$ are the p.u.l. impedance matrix and the p.u.l. admittance matrix on the k-th segment, respectivey.

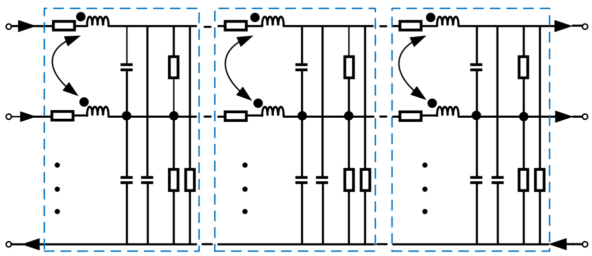

Fig. 3. Coplanar irregular-placed cables equivalent circuit model.

Assuming that the height of the cable is a constant, the equivalent circuit diagram is shown in Fig. 4. Coplanar irregular-placed cables are divided into m segment (m is large enough).

For the k-th segment of the differentiated cable, (3) is also acceptable. (3) is further simplified to:

$$\frac{d}{dz}\bar{\boldsymbol{F}}(k)=\boldsymbol{T}_k\bar{\boldsymbol{F}}(\mathrm{k}), \tag{4}$$

where $\bar{\boldsymbol{F}}(\mathrm{k})=\begin{bmatrix}\bar{\boldsymbol{U}}(k)\\ \bar{\boldsymbol{I}}(k)\end{bmatrix}$, $\boldsymbol{T}_k=\begin{bmatrix}0 & -\boldsymbol{Z}_k\\ -\boldsymbol{Y}_k & 0\end{bmatrix}$.

The matrix $\bar{\boldsymbol{F}}(\mathrm{z})$ on the k-th segment is left multiplied by $\boldsymbol{e}^{-\boldsymbol{T}_k\cdot z}$ and differentiated by the length z:

$$\frac{d}{dz}\boldsymbol{e}^{-\boldsymbol{T}_k\cdot z}\bar{\boldsymbol{F}}(z)=0\,. \tag{5}$$

So the integral at $[k,k+\Delta z]$ is:

$$\int_k^{k+\Delta z}\frac{d}{dz}\boldsymbol{e}^{-\boldsymbol{T}_k\cdot z}\bar{\boldsymbol{F}}(z)=0\,. \tag{6}$$

Then,

$$\boldsymbol{e}^{-\boldsymbol{T}_k\cdot(\Delta z+k)}\bar{\boldsymbol{F}}(k+\Delta z)-\boldsymbol{e}^{-\boldsymbol{T}_k\cdot k}\bar{\boldsymbol{F}}(k)=0\,. \tag{7}$$

The solution of the first-order differential equations in the k-th segment is:

$$\bar{\boldsymbol{F}}(k+\Delta z)=\boldsymbol{e}^{-\boldsymbol{T}_k\cdot\Delta Z}\bar{\boldsymbol{F}}(\mathrm{k})\,. \tag{8}$$

Since the length of each segment is extremely short and the z is extremely small after the cable is differentiated, then T_k can be considered equal to T_{k+l}, so there is:

$$\bar{\boldsymbol{F}}(\boldsymbol{d})=\boldsymbol{e}^{-\sum_{i=1}^{m}\boldsymbol{Ti}}\bar{\boldsymbol{F}}(0)=\boldsymbol{e}^{-\int_0^d \boldsymbol{T}(z)\cdot d\boldsymbol{z}}\bar{\boldsymbol{F}}(0)\,. \tag{9}$$

Therefore, the solution of the first-order cable crosstalk can be expressed as:

$$\begin{bmatrix}\bar{\boldsymbol{V}}(d)\\ \bar{\boldsymbol{I}}(d)\end{bmatrix}=exp\left\{\int_0^d\begin{bmatrix}0 & -\boldsymbol{Z}\\ -\boldsymbol{Y} & 0\end{bmatrix}\mathrm{dz}\right\}\begin{bmatrix}\bar{\boldsymbol{V}}(0)\\ \bar{\boldsymbol{I}}(0)\end{bmatrix}. \tag{10}$$

For regular-placed cables, the $\boldsymbol{T_k}$ of different segments is equal since each segment has the same p.u.l. parameter matrix. The electromagnetic matrix formula can be expressed as:

$$\int_0^d\begin{bmatrix}0 & -\boldsymbol{Z}\\ -\boldsymbol{Y} & 0\end{bmatrix}\mathrm{dz}=d*\begin{bmatrix}0 & -\boldsymbol{Z}\\ -\boldsymbol{Y} & 0\end{bmatrix}. \tag{11}$$

Similar with the electromagnetic matrix formula (11) of the regular cable above, the equivalent electromagnetic matrix $\boldsymbol{Z}_d$, $\boldsymbol{Y}_d$ and $\boldsymbol{T}_d$ of coplanar irregular-placed cables can be expressed as:

$$\boldsymbol{Z}_d=\int_0^d \mathrm{Zdz}\Big/d\,, \tag{12}$$

$$\boldsymbol{Y}_d=\int_0^d \mathrm{Ydz}\Big/d\,, \tag{13}$$

$$T_d=\begin{bmatrix}0 & \boldsymbol{Z}_d\\ \boldsymbol{Y}_d & 0\end{bmatrix}=\int_0^z\begin{bmatrix}0 & \boldsymbol{Z}\\ \boldsymbol{Y} & 0\end{bmatrix}\mathrm{dz}\Big/d\,. \tag{14}$$

It is noteworthy that the integral equation can be solved more accurately when the equivalent electromagnetic matrix $\boldsymbol{Z}_\mathrm{d}$ and $\boldsymbol{Y}_\mathrm{d}$ are calculated by the function method. Therefore, the solution of the crosstalk of coplanar irregular-placed cables can be divided into two steps. The first step is to calculate the equivalent electromagnetic parameter matrix to make coplanar irregular-placed cables equivalent to regular cables. The second step is to predict the crosstalk of coplanar irregular-placed cables by using the method of crosstalk prediction for regular cables under ideal conditions.

III. COPLANAR IRREGULAR-PLACED CABLES PARAMETER MATRIX AND CROSSTALK INFLUENCING FACTORS

A. Calculation of coplanar irregular-placed cables parameter matrix based on cubic spline interpolation

In the crosstalk study of MTL, the resistance and conductance values of the transmission line are usually negligible relative to the terminal load resistance value. The inductance depends on the permeability of the surrounding medium and is independent of the dielectric constant of the medium [10]. In practical applications, the transmission line is usually laid on materials such as aluminum, copper and PCB (usually FR-4) with almost constant magnetic permeability. The inductance parameter matrix $\boldsymbol{L}$ of the n cores MTL on the return surface can be expressed as:

$$L=\begin{bmatrix}l_{11} & l_{12} & \cdots & l_{nn}\\ l_{21} & l_{22} & \cdots & l_{2n}\\ \vdots & \vdots & \ddots & \vdots\\ l_{n1} & l_{n2} & \cdots & l_{nn}\end{bmatrix}, \tag{15}$$

$$l_{ii}=\frac{\mu}{2\pi}\ln(\frac{2h_i}{r_{wi}})\,, \tag{16}$$

$$l_{ij}=\frac{\mu}{2\pi}\ln(1+\frac{4h_ih_j}{s_{ij}^2})\,, \tag{17}$$

where i and j are positive integer, and i, j∈[1,n]. The permeability of the medium is represented by μ. The heights of the i-th and j-th conductors from the ground are represented by h_i and h_j, respectively. The distance between the i-th and j-th conductor is denoted by s_{ij}. The radius of the i-th conductor is indicated by r_{wi}.

Observing (14), the solution of the equivalent electromagnetic parameter matrix can be transformed into the integral calculation of the electromagnetic parameter matrix.

The inductance parameter matrix is easy to solve its integral in the form of an analytical form, specifically:

$$\boldsymbol{L}_d = \int_0^d \mathrm{L}dz = j\omega \int_0^d \begin{bmatrix} l_{11} & l_{12} & \cdots & l_{nn} \\ l_{21} & l_{22} & \cdots & l_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ l_{n1} & l_{n2} & \cdots & l_{nn} \end{bmatrix} \mathrm{d}z\,, \tag{18}$$

where $\boldsymbol{L}_d$ equivalent inductance matrix.

However, the capacitance parameter matrix $\boldsymbol{C}$ is sensitive to the dielectric constant and is difficult to express with an analytical expression. Therefore, it is impossible to directly solve the integral of capacitance matrix $\boldsymbol{C}$ of each differential segment by using a function method similar to the inductance matrix, such as (19):

$$\boldsymbol{C}_d = \int_0^d \mathrm{C}dz = j\omega \int_0^d \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{nn} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ c_{n1} & c_{n2} & \cdots & c_{nn} \end{bmatrix} \mathrm{d}z\,, \tag{19}$$

where $\boldsymbol{C}_d$ is the capacitance matrix.

The capacitance matrix of each differential segment can be solved by ANSYS Q3D based on the finite element method (FEM), but only the equivalent capacitance matrix at some specific points on the coplanar irregular-placed cables can be obtained. Therefore, this paper combines the cubic spline interpolation under the condition of no twist to solve the capacitance matrix integral.

Take the element c_{11} in the capacitance matrix as an example. The distance from the midpoint of each segment to the starting point is recorded as [z_1, z_2, …, z_k, z_{k+1}, …, z_{m-1}, z_m], and use the FEM method to solve the corresponding c_{11}. The continuous function G(z) on parameter c_{11} is established, G(z)=c_{11}(z) can be expressed as:

$$G(z) = G_1(z) + G_2(z) + \cdots + G_m(z)\,, \tag{20}$$

$$G_k(z) = a_k z^3 + b_k z^2 + c_k z + d_k\,,\ \ z \in [z_k, z_{k+1}]\,, \tag{21}$$

where k is a positive integer, k∈[0, m]. The parameters a_k, b_k, c_k and d_k stand for the coefficients corresponding to the third to zero terms.

Similar to c_{11}, other elements in the capacitance parameter matrix $\boldsymbol{C}$ are treated by this method. The capacitance parameter matrix $\boldsymbol{C}$ of the cables can be easily solved by using (19).

B. Orthogonal experiment on the influencing factors of the crosstalk

As shown in Table 1, the orthogonal experimental method is used to qualitatively compare the main influencing factors of crosstalk (distance between cables, length of cables, the height of cables from ground and the terminal load of cables), and add frequency as the contrast factor. The above factors are divided into four levels, each of which corresponds to different values, in which frequency is divided by its order of magnitude (logarithm).

Table 1: Orthogonal experimental factors

Levels	1	2	3	4
Length/cm	50	100	150	200
Height from the ground/cm	1.25	2.5	3.75	5
Distance between cables/cm	1.25	2.5	3.75	5
Load/Ω	25	50	75	100
Frequency logarithm	6	7	8	9

The 16 sets of crosstalk under the regular-placed cables model are calculated, and the data obtained are put into the orthogonal table specially used for orthogonal experiment method. The results are shown in Table 2.

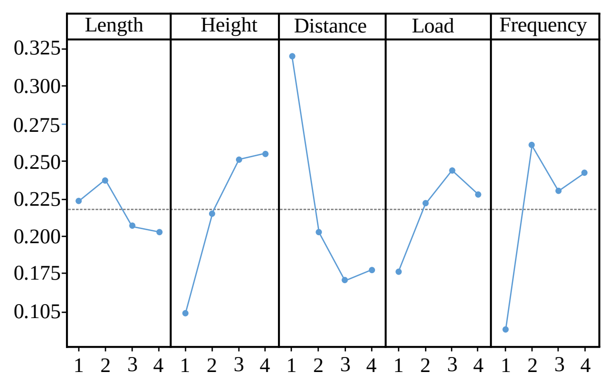

Fig. 3. Main effect diagram of orthogonal experiments.

From the main effect diagram Fig. 4, it can be seen that in the physical condition of the cable in this paper, the distance between cables has the greatest influence on crosstalk, followed by the height, frequency, load, length, etc. Therefore, the sampling points with large distance variation between cables should be selected as much as possible, followed by the height from the ground.

VI. VERIFICATION AND ANALYSIS

In order to describe the convenience of the new method, two long straight coplanar irregular-placed cables on the return surface is taken as an example to verify the effectiveness of this method. The relevant parameters of cables are shown in Table 3. The frequency band for solving crosstalk is 1MHz - 1GHz.

Table 2: The orthogonal experiment scheme

No.	Factors					Crosstalk
	Length/ cm	Height/ cm	Distance/ cm	Load/ Ω	Frequency Logarithm	
1	50	1.25	1.25	25	6	-39.834
2	50	2.5	2.5	50	7	-27.416
3	50	3.75	3.75	75	8	-27.871
4	50	5	5	100	9	-27.305
5	100	1.25	2.5	75	9	-31.663
6	100	2.5	1.25	100	8	-20.452
7	100	3.75	5	25	7	-29.243
8	100	5	3.75	50	6	-37.589
9	150	1.25	3.75	100	7	-38.561
10	150	2.5	5	75	6	-44.325
11	150	3.75	1.25	50	9	-19.866
12	150	5	2.5	25	8	-32.028
13	200	1.25	5	50	8	-44.025
14	200	2.5	3.75	25	9	-39.620
15	200	3.75	2.5	100	6	-37.597
16	200	5	1.25	75	7	-17.816

Table 3: Physical parameters of cables

Parameters	Values
Cable diameter	1mm
Thickness of insulation layer	0.65mm
The height from the ground	50mm
Length of harness	1m
Minimum distance between cables	25mm
Maximum distance between conductors	50mm
Relative permittivity of insulation lay	3.5
Relative permeability of conductor	1.0

The important electromagnetic matrices in this paper include the inductance matrix and the capacitance matrix. Since the inductance parameter is independent of the insulation layer, each parameter of the inductance matrix can be calculated according to the (16) and (17). However, the capacitance parameter matrix mentioned in the previous section cannot be directly calculated by the analytical formula.

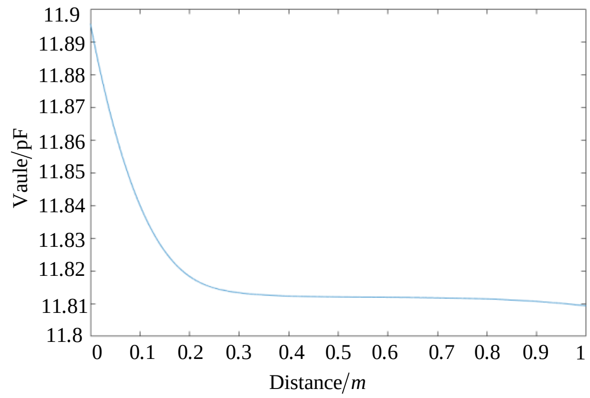

Fig. 5. The self-capacitance (c_{11} or c_{22}).

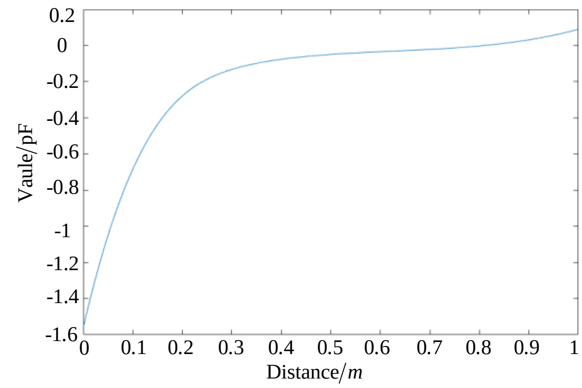

Fig. 6. The mutual capacitance (c_{12} or c_{21}).

The processing of the capacitance parameter matrix is as follows. Firstly, the FEM method is used to solve the capacitance matrix C of different transmission line distance, and the solution points are 50 points of equal distance on the transmission line. Then, the self-capacitance elements c11 and c22 and the mutual capacitance elements c12 and c21 in the capacitance matrix are fitted by cubic spline interpolation method. The fitting results are shown in Fig. 5 and Fig. 6. Among them, the physical parameters of the cables are the same, so c11=c22. And the parameter matrix C is a symmetric matrix, so c12=c21.

The calculated equivalent inductance matrix $\boldsymbol{L}_d$ and the capacitance matrix $\boldsymbol{C}_d$ based on the electromagnetic parameters of all sampling points are:

$$\boldsymbol{L}_d = \begin{bmatrix} 1059.7 & 25.138 \\ 25.138 & 1059.7 \end{bmatrix} nH \quad \boldsymbol{C}_d = \begin{bmatrix} 11.813 & -0.098 \\ -0.098 & 11.813 \end{bmatrix} pF \,. \tag{22}$$

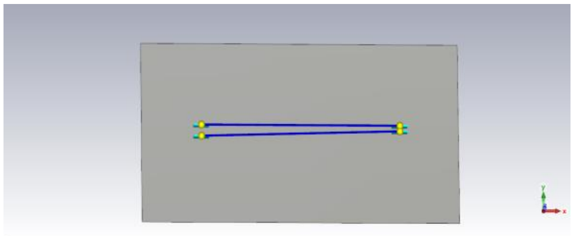

Fig. 7. CST model of coplanar irregular-placed cables.

The full wave simulation of the CST Cable Studio® commercial software - the transmission line matrix (TLM) method, an electromagnetic field numerical method based on the Huygens wave propagation model, is used to solve the crosstalk results as a reference standard in this paper. The simulation model of CST are shown in Fig. 7.

In order to verify the effectiveness of the algorithm, the experimental bench is set as shown in Fig. 8 and Fig. 9. The experimental equipment mainly includes R&S ZVL3 Vector Network Analyzer (VNA), a return plane of a tin-plated copper sheet and two boards for fixing wires.

Fig. 8. Photo of experiment.

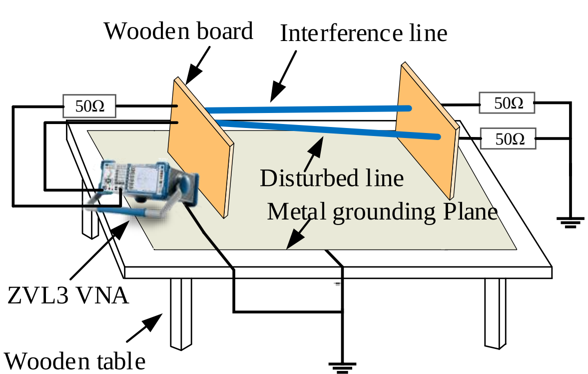

Fig. 9. Experimental configuration diagram.

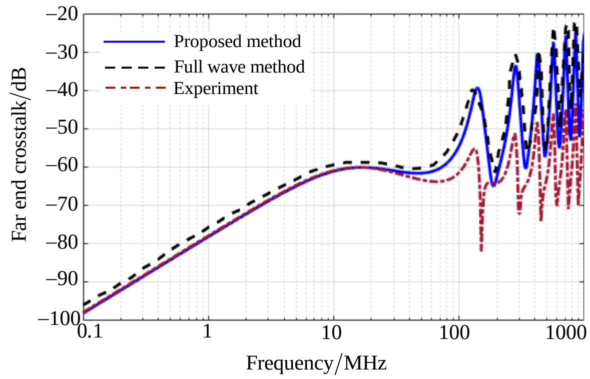

Fig. 10. Far end crosstalk of coplanar irregular-placed cables.

The crosstalk results solved by different methods are shown in Fig. 10. The error of some frequency points are shown in Table 4. In the frequency band of 0.1 MHz - 30 MHz, the error between the new method and the experimental results is much smaller than the error between the full wave method and the experimental results. The maximum error between the new method and the experiment is -0.58dB. In the frequency band of 30 MHz - 100 MHz, the error of the new method is larger than the error of the new method in the low frequency band, but the result of the new method still has higher precision than the full wave method. In the frequency band of 100 MHz - 1000 MHz, the new method and the full wave method are consistent with the trend of the experimental results, but the error is significantly increased. In conclusion, the new method has a higher accuracy for the far end cross of coplanar irregular-placed cables, especially in the low frequency range.

Table 4: Error solving by different methods

Frequency/ MHz	Experiment	Full Wave Method		Proposed Method	
	Value/dB	Value/dB	Error/dB	Value/dB	Error/dB
0.1	-97.53	-95.91	-1.62	-96.95	-0.58
1	-77.95	-75.46	-2.49	-77.81	-0.14
10	-60.84	-59.43	-1.41	-60.54	-0.30
100	-61.76	-50.20	-11.56	-54.85	-6.91
1000	-45.10	-28.41	-16.69	-28.34	16.76

In the high frequency band, the error accuracy of the new method and the full wave method is significantly increased because of the non-ideality of the experimental conditions, such as the transmission line (the transmission line may not be completely coplanar due to gravity), the terminal resistance, VNA. Although each factor alone has little effect on the value of the far end crosstalk, the effect of all factors on the actual crosstalk cannot be neglected.

V. CONCLUSION

A new method for predicting crosstalk of coplanar irregular-placed cables is presented in this paper. The crosstalk prediction method of coplanar irregular-placed cables based on the theory of cascade transmission line and the cubic spline interpolation algorithm is studied with the research method of regular-placed cables as a reference. And the orthogonal experiment method is used to compare and analyze the factors affecting the crosstalk of the transmission line. The analysis results show that the distance between the transmission lines has the greatest influence on crosstalk, followed by the height from the current return plane, frequency, load, length. In this paper, the far end crosstalk of coplanar irregular-placed cables is verified and analyzed by the new method, full wave method and experiment. Compared with the full wave method, the new method has better solution accuracy. Specifically, the maximum errors between the new method and experiment are -0.58 dB and -6.91 dB in the frequency band of 0.1 MHz - 30 MHz and 30 MHz - 100 MHz, respectively.

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