Analysis of Coupling Effectiveness on Concealed Signal Cable Slot with Different Shapes

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Abstract: It is important to study the shielding effectiveness to reduce the electromagnetic interference and to protect electronic components. Taking the concealed signal cable which is set in shielding shell as the research object. The influence of different slot shapes on shielding effectiveness was analyzed by applying the mixed methods (Quadric FE-BEM). The results show that the coupling capacitance of a trapezoidal slot is the biggest, the one of rectangular slot is medium, and the one of a taper slot is the smallest for shielding pair cable, but their change trend are almost the same. In addition, with the various slot shapes width increasing, shielding pair cable coupling capacitance is little changed. The study is instructive for more effective to defense EMI and will improve the agricultural concealed shielding cable electromagnetic compatibility.

Keywords: Concealed signal cable, Slot with different shapes, Coupling capacitance, the mixed methods (Quadric FE-BEM).

1. Introduction

With the rapid development of electronic technique, the concealed signal cable has widely used in many important equipment connections, such as fire fighting equipment, communications equipment, etc. [1]. However, the problem of electromagnetic interference becomes more and more serious [2-4]. The shielding layer is an effective method to reduce the electromagnetic interference, but there are inevitable slit or slot of different hole patterns in the shielding layer, to connect the power lines, ventilate, or for other purpose. These slots can reduce shielding effectiveness of the shielding layer, which can make the electromagnetic wave coupled into the signal cable, affecting the regular work of the electronic equipments. Therefore it is necessary to study the coupling characteristics of various slot shapes to reduce the interference of electromagnetic wave.

Concealed cables [5] are one of the important parts of the whole system that used for wiring domestic and commercial buildings, and undertake the arduous task of signal transmission. Under extreme circumstances, the coupling capacitances of core wires in electronic devices could be determined only when parameters such as inductances [6-7] and capacitances were given [8-12]. Thus, the coupling characteristics of the concealed signal cables containing circumferential weld shields must be studied to minimize the disturbances of electromagnetic waves.

At present, there were many studies on the concealed cables, and the methods were varied, such as Multi-pole theory [13], FDTD [14], MOM [15] and transmission line method [5, 16]. However, the study on the influence of coupling capacitance effect of concealed cable with different slot shapes is far from enough. In most cases, the slots on the shielding...
layer are not single slots. In this paper, with the concealed shielded coaxial cable and the two-core cable as the research objects, the influence of different slot shapes (such as taper slot, trapezoidal slot, rectangular slot) in shielded effectiveness were analyzed by applying the mixed methods (Quadric FE-BEM) [17-19] with Matlab [20-25]. To demonstrate the accuracy and flexibility of the mixed methods, the influence of the deformation degree of shielded deformed coaxial cable compared with the multi-pole theory and others on the results were discussed. The engineering example results showed that for the concealed signal two-core cable, the change of coupling capacitance was related with the slot shapes in deep layer at the location of parallel core distance; and the change tendency of coupling capacitor with the slot shapes at the vertical core distance was almost the same as the slots at the parallel core distance. But, when the slots depth was quite deep, very likely one core was exposed, and then the coupling capacitor decreased rapidly. Therefore the study was instructive for more effective to defense EMI and would improve the concealed signal cable electromagnetic compatibility.

2. Mixed Method (Quadric FE-BEM)

2.1. Quadric FEM

A triangle element about quadric FEM have six nodes (includes three vertices and a middle node of each sides). As shown in Fig. 1, suppose \( u \) that a node field in triangle element is quadric interpolating of the fields about six nodes [19]:

\[
\begin{align*}
    u &= c_1 + c_2 x + c_3 y + c_4 x^2 + c_5 y^2 + c_6 x y \\
    &= \sum_{i=1}^{6} c_i f_i, \quad f_i = x^k y^l, \quad k + l \leq 2
\end{align*}
\]

The \( u(E_x \ or \ H_z) \) (longitudinal components of fields) should meet Helmholtz equation, when waves tracing in the metal waveguide [19].

\[
\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + k_{ij}^2 u = 0 \tag{2}
\]

Equivalent functional is

\[
J(u) = \int_s \left[ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial u}{\partial y} \right)^2 - k_{ij}^2 u^2 \right] dx dy \tag{3}
\]

Discrete (3), maximized functional, is:

\[
K_p u_i + K_p u_t + \cdots + K_p u_n = k_{ij} \left( B_p u_1 + B_p u_2 + \cdots + B_p u_n \right) \tag{4}
\]

Matrix form is consisted of every coefficient is:

\[
\begin{align*}
    [K^Q] &= [Q_1] \ c t g \theta + [Q_2] \ c t g \theta_j \\
    &+ [Q_m] \ c t g \theta_m
\end{align*}
\]

In (5), \([K^Q][B^Q]^T\) are the symmetrical matrix, \([Q_1],[Q_2],[Q_m],[B]\) are the constants.

2.2. Quadric BEM

A 2-dimension boundary integral equation is derived by Green's theorem [4]:

\[
C_p u(\bar{r}) = \int_{\Gamma_1} \left( \frac{\partial u}{\partial n} - q \frac{\partial G}{\partial n} \right) \bar{r}' d\Gamma' \\
+ \int_{\Gamma_2} \left( q G - u \frac{\partial G}{\partial n} \right) \bar{r} d\Gamma
\]  

Quadric segment of QBEM, as shown in Fig. 2, a element is discrete 2 segments (3 nodes), \( u \) and \( q \) of three nodes means \( u_1, q_1, u_2, q_2 \) and \( u_3, q_3 \), next, interrelated nodal value and \( \phi_1, \phi_2, \phi_3 \) quadric function can be used to represent any point of \( u \) and \( q \), namely [4]:

\[
\begin{align*}
    u(\xi) &= \phi_1 u_1 + \phi_2 u_2 + \phi_3 u_3 = \left[ \begin{array}{c} 1 \\ u_1 \\ u_2 \end{array} \right] \left[ \begin{array}{c} \phi_1 \\ \phi_2 \\ \phi_3 \end{array} \right] \\
    q(\xi) &= \phi_1 q_1 + \phi_2 q_2 + \phi_3 q_3 = \left[ \begin{array}{c} 1 \\ q_1 \\ q_2 \end{array} \right] \left[ \begin{array}{c} \phi_1 \\ \phi_2 \\ \phi_3 \end{array} \right]
\end{align*}
\]

where \( \phi_1, \phi_2, \phi_3 \) are the \( \xi \) quadratic function.

\[
\begin{align*}
    \phi_1 &= \frac{1}{2} \xi(\xi - 1) \\
    \phi_2 &= \frac{1}{2} \xi(\xi + 1) \\
    \phi_3 &= (1 - \xi)(1 + \xi)
\end{align*}
\]

Equivalent functional is
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Abbreviated formula was:

$$\tilde{A} \tilde{X} = \tilde{B},$$

(13)

where $\tilde{A}$ is the $N \times N$ rank phalanx, $\tilde{X}$ and $\tilde{B}$ are the $N$ rank array. Equation (13) is the equation of linear boundary element method.

2.3. Mixed Method (Quadric FE- BEM)

Solving of the two-dimensional Laplace equation is taken as an example. Assume that there is an area $\Omega$ with uniform medium as shown in Fig. 3, in which, the finite element method analysis (FEM) is used in area $\Omega_{F}$, while the boundary element method (BEM) in area $\Omega_{B}$. And $\Omega = \Omega_{F} + \Omega_{B}$.

As shown in Fig. 3, Using the finite element method analysis in area $\Omega_{F}$, matrix equation could always be obtained as follows:

$$K \begin{bmatrix} U_{F} \\ U_{F}^{L} \end{bmatrix} = \begin{bmatrix} P_{F} \\ P_{L} \end{bmatrix},$$

(14)

where $U_{F}$ is the bit vector of the node of $\Omega_{F}$ and $\Gamma_{F}$; $P_{F}$ is the external excitation vector acting at the node of $\Gamma_{F}$. And both $U_{F}^{L}$ and $P_{L}$ are vectors on the internal boundary $\Gamma_{L}$.

Using boundary element method on the boundary $\Gamma_{B} + \Gamma_{L}$ of area $\Omega_{B}$, the resultant algebraic equation is generally shown in the following form:

$$H \begin{bmatrix} U_{B} \\ U_{B}^{L} \end{bmatrix} = Q \begin{bmatrix} Q_{B} \\ Q_{B}^{L} \end{bmatrix},$$

(15)

where $U_{B}$ and $Q_{B}$ are the electrical potential of the node on $\Gamma_{B}$, and the vector consisted by its derivative.

In equation (10), values of $N_{1} u_{j}$ on $I_{k1}$ and $N_{2} q_{j}$ on $I_{k2}$ were given by boundary condition, shown them with $\tilde{u}_{0}(N_{1})$ and $\tilde{q}_{0}(N_{2})$; values of $N_{1} \partial u / \partial n'$ on $I_{k1}$ and $N_{2} u$ as uncertain variate, shown them with $\tilde{q}_{1}(N_{1})$ and $\tilde{u}_{1}(N_{2})$. Then equation (7) could be expressed as the following block matrix

$$\begin{bmatrix} \tilde{H}_{0} & \tilde{G}_{1} \\ \tilde{G}_{0} & \tilde{H}_{1} \end{bmatrix} \begin{bmatrix} \tilde{u}_{0}(N_{1}) \\ \tilde{u}_{0}(N_{2}) \end{bmatrix} + \begin{bmatrix} \tilde{G}_{0} & \tilde{G}_{1} \\ \tilde{G}_{0} & \tilde{G}_{1} \end{bmatrix} \begin{bmatrix} \tilde{q}_{0}(N_{2}) \\ \tilde{q}_{1}(N_{1}) \end{bmatrix} = 0.$$  

(11)

If the uncertain terms were put on the left of the equation, and the certain terms were put on the right of the equation, then equation (11) could be changed into the following:

$$\begin{bmatrix} \tilde{H}_{1} & \tilde{G}_{1} \\ \tilde{G}_{1} & \tilde{H}_{0} \end{bmatrix} \begin{bmatrix} \tilde{u}_{1}(N_{2}) \\ \tilde{q}_{1}(N_{1}) \end{bmatrix} = - \begin{bmatrix} \tilde{C}_{0} & \tilde{H}_{0} \\ \tilde{G}_{0} & \tilde{G}_{1} \end{bmatrix} \begin{bmatrix} \tilde{q}_{0}(N_{2}) \\ \tilde{u}_{0}(N_{1}) \end{bmatrix}.$$  

(12)
in the normal direction, respectively. And $U^L_B$ and $Q^L_B$ are vectors on the internal boundary $\Gamma_L$.

Areas $\Omega_F$ and $\Omega_B$ share a common boundary $\Gamma_L$. Considering that $P$ is related to $Q$, the electrical potentials on both sides of $\Gamma_L$ and the vectors of their derivatives on the normal direction shall satisfy the compatibility condition and equilibrium condition, respectively:

$$U^L_B = U^L_F, \quad Q^L_B = -Q^L_F \quad (16)$$

The simultaneous equations of (14) and (15) are solved, and unknown quantities could be theoretically determined. If the $\varepsilon_B$ and $\varepsilon_F$ of $\Omega_B$ and $\Omega_F$ media are different, the equilibrium condition should be changed into $\varepsilon_B Q^L_B = -\varepsilon_F Q^L_F$.

Assume that there is an area $\Omega$ with a boundary $\Gamma = \Gamma_1 + \Gamma_2$. The $u$ is given on $\Gamma_1$, whereas the $q$ is known on $\Gamma_2$. For the full boundary $\Gamma$, the basic relationship of boundary element method is defined as:

$$\int_\Omega (\nabla u) Wd\Omega = \int_{\Gamma_1} (q - \bar{q}) Wd\Gamma - \int_{\Gamma_2} (u - \bar{u}) \frac{\partial W}{\partial n} d\Gamma$$

Integration by parts is performed twice on the equation above, and thus obtaining:

$$\int_\Omega (\nabla^2 W) d\Omega = -\int_{\Gamma_2} \bar{q} Wd\Gamma - \int_{\Gamma_1} q Wd\Gamma + \int_{\Gamma_1} u \frac{\partial W}{\partial n} d\Gamma + \int_{\Gamma_2} \bar{u} \frac{\partial W}{\partial n} d\Gamma$$

If $W$ is the basic solution $u^*$ of the question, the following equation to the boundary point $i$ should be as follow:

$$C_i u_i + \sum_j u \frac{\partial u^*}{\partial n} d\Gamma = \sum_j qu^* d\Gamma$$

After discretization, a systemic matrix equation set to boundary $\Gamma$ should be as follow:

$$HU_i = GQ \quad (17)$$

The boundary condition is not considered in the equation above, and it is a classic algebraic equation set based on boundary element method. Where both $U_i$ and $Q$ are vectors of node on the boundary.

On the other hand, the finite element analysis is used for the same area $\Omega$. Firstly, start from the following equation:

$$\int_\Omega (\nabla^2 u) \delta u d\Omega = \int_{\Gamma_2} (q - \bar{q}) \delta u d\Gamma \quad (18)$$

Assume that function $u$ satisfies the basic boundary $\Gamma_1$ condition of $u = \bar{u}$. Integration by parts on equation (18) once, thus obtaining:

$$\int_\Omega \frac{\partial u}{\partial n} \frac{\partial \delta u}{\partial n} d\Omega = \int_{\Gamma_2} \bar{q} \delta u d\Gamma$$

The matrix algebraic equation set based on finite element analysis, corresponding to equation (19), is:

$$\partial U^T_2 KU_2 = \delta U^T_2 P \quad (20)$$

$$KU_2 = P \quad (21)$$

Equation (21) is the classic algebraic equation set based on finite element analysis.

In equation (21), $U_2$ is the electrical potential of all the nodes in area $\Omega$ and on the boundary $\Gamma$; $K$ is the matrix that only related to the geometrical shape and size of various elements; $P$ is the vector obtained through calculating the boundary integrals on the right of equation (19).

If the area $\Omega$ is exactly $\Omega_F$, equation (21) could be in the form of block vectors, i.e., equation (14).

$P$ and $Q$ are the vectors in the equation obtained by the two methods used for the same area, and they are derived by the same line integral. Thus, they are certainly related.

$U^T_2 P$ represents the excitation provided by the external source on boundary $\Gamma_2$ to the system. During the finite element partition of $\Omega$, the boundary $\Gamma$ is also partitioned into segments, and they belong to each finite element, respectively. If regarding these boundary segments as elements, the following equation could be obtained:

$$\delta U^T_2 P = \sum_j (\int_{\Gamma_j} q \delta u d\Gamma) \quad , \quad (22)$$

where $(j)$ is the element number on boundary $\Gamma_2$.

Functions $u$ and $q$ could be approximately expressed by interpolation function and nodal value on boundary element $(j)$ as:

$$u = u^T(j) \phi$$
$$q = \psi^T q(j)$$
where \( u(j) \) and \( q(j) \) represent the nodal electrical potential on boundary element \((j)\) and the vector of its derivative on the normal direction, respectively. Substitute the two equations above into equation (21), thus obtaining:

\[
\delta U^T P = \sum_j \left[ \delta u^T(j) \left( \int_{\Gamma_j} \phi \psi^T d\Gamma \right) q(j) \right]
\]

In order to bring the vector \( u(j) \) on boundary element \((j)\) into \( U \) of the full system (including interior area), and bring \( q(j) \) into the vector \( Q \) of the node of full boundary (excluding the interior area), the Boole matrix is used.

\[
\delta u(j) = a B(j) \cdot \delta U, \quad q(j) = B(j) \cdot Q
\]

If element \((j)\) has \( N \) nodes and the entire area (inducing the boundary) has a total of \( N \) nodes, \( a B(j) \) is a \( N \times N \) order matrix. They all consist of 0 or 1. Nonzero elements are memoried only in calculation, as in the similar case of \( a B(j) \). Whereas it could only establish connection between boundary element \((j)\) and the full boundary. Two equations above are used and then the following equation could be obtained:

\[
\delta U^T P = \sum_j \left[ \delta U^T \left( a B(j)^T \int_{\gamma_j} \phi \psi^T d\Gamma \right) B(j) \right] Q
\]

\[
= \delta U^T MQ
\]

Therefore

\[
P = MQ \tag{23}
\]

Thus equation (21) could be as follow:

\[
KU^T = MQ \tag{24}
\]

For a combined solution to equate a finite element analysis-based area \( \Omega_F \) into a boundary element method-based equation set, which could be written in a block form as following:

\[
\begin{bmatrix}
K_F K_F^T
\end{bmatrix}
\begin{bmatrix}
U_F
\end{bmatrix}
= \begin{bmatrix}
M_F M_F^T
\end{bmatrix}
\begin{bmatrix}
Q_F
\end{bmatrix}
\tag{25}
\]

On the other hand, in boundary element area \( \Omega_B \) (including \( \Gamma_I \) and \( \Gamma_F \)), equation set is equation (15), which could be written as following after conversion:

\[
\begin{bmatrix}
H_B H_B^T
\end{bmatrix}
\begin{bmatrix}
U_B
\end{bmatrix}
= \begin{bmatrix}
G_B G_B^T
\end{bmatrix}
\begin{bmatrix}
Q_B
\end{bmatrix} \tag{26}
\]

Based on equation (25) and (26), and taking into consideration of the compatibility condition and equilibrium condition,

\[
U^I = U^F = U^I, \quad Q^I = -Q^F = Q^I \tag{27}
\]

The boundary element method-based system equation of the entire area \( \Omega \) could be obtained:

\[
\begin{bmatrix}
H_B H_B^T & -G_B^T \\
G_B & 0
\end{bmatrix}
\begin{bmatrix}
U_B \\
Q_B
\end{bmatrix}
= \begin{bmatrix}
M_F & M_F^T \\
0 & M_F
\end{bmatrix}
\begin{bmatrix}
Q_F \\
Q_I
\end{bmatrix} \tag{28}
\]

Substitute the boundary condition into the equation above, the unknown quantities could thus be determined.

3. Concealed Cable Capacitance Calculation Principle

3.1. Cable Capacitance Coupling Mechanism

Capacitive coupling is the electromagnetic interference phenomenon which caused by distributed capacitance between the electronic devices, electronic components, PCB line, and so on. The capacitance would be existed between the two conductors when they close to each other. And the conductive pathway would be formed through this reactance. This phenomenon is called capacitance coupling that the potential of other conductors were effect by the signals voltage (or noise voltage) of conductor through distributed capacitance, namely, electrostatic coupling or electrostatic induction.

The characteristic impedance \( Z_0 \) of TEM transmission line as follows:
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$$Z_0 = (v_0 C_0)^{-1},$$

where \( v_0 = 1/\sqrt{\mu_0} \), the capacitance \( C_0 \) is computed at first. The signal would be reflex in the node of impedance discontinuity if the impedance of the transmission path had changed during the signal transmission. Thus, the changes of coupling capacitance are closely with electromagnetic interference, which would be affecting the quality of the signal transmission.

### 3.2. Concealed Cable Capacitance Calculation Principles

One of the main works of the electromagnetic compatibility analysis in the system is to calculate the capacitance coupling of guide line to core wire, thus, the coupling capacitance and free capacitance are computed at first. As shown in Fig. 4, assume the shielded structure (conductor 0) is zero potential conductors, and the potentials of the other \( N \) conductors are respectively \( V_1, V_2, \ldots, V_N \), then the boundary value problems of electrostatic field as follows

$$\begin{cases} \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial u}{\partial r} \right) + \frac{\partial^2 u}{\partial \theta^2} = 0, r, \theta \in \Omega \\ u|_0 = 0, u|_{l_i} = V_i, u|_{l_k} = V_N, \quad i = 1, 2, \ldots, N \end{cases}$$

where \( \Omega \) is the field, \( l_k \) is \( k \) conductor boundary curve of \( k \) conductor, \( V_i \) is \( k \) conductor potential.

![Fig. 4. Various shielding cable.](image)

The capacitance matrix of shielded multi-conductor cable is

$$\begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \vdots \\ \lambda_N \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1N} \\ C_{21} & C_{22} & \cdots & C_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ C_{N1} & C_{N2} & \cdots & C_{NN} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix},$$

(30)

where \( C_{ij} = \left( \frac{\lambda_j}{V_j} \right) \bigg|_{V_j=0, V_j=0} \) are free capacitances.

$$C_y = \left( \frac{\lambda_j}{V_j} \right) \bigg|_{V_j=0, V_j=0}$$

are coupling capacitance.

### 3.3. Matlab Introduction

Matlab was both a powerful computational environment and a programming language that easily handles matrix and complex arithmetic. It was a large software package that has many advanced features built-in, and it had become a standard tool for many working in science or engineering disciplines. Among other things, it would allow easy plotting in both two and three dimensions.

Matlab had two different methods for executing commands: interactive mode and batch mode. In interactive mode, commands are typed (or cut-and-pasted) into the ‘command window’. In batch mode, a series of commands were saved in a text file (either using Matlab’s built-in editor, or another text editor such as Emacs) with a ‘.m’ extension. The batch commands in a file were then executed by typing the name of the file at the Matlab command prompt. The advantage to using a ‘.m’ file was that you could make small changes to your code (even in different Matlab sessions) without having to remember and retyping the entire set of commands. Also, when using Matlab’s built-in editor, there were simple debugging tools that can come in handy when your programs start getting large and complicated. More on writing .m files later.

### 4. Analyzed Results

#### 4.1. Comparison of Theory and the Multi-pole Theory

As shown in Fig. 5, a cross-section of long straight cable, where \( r \) means radius of circular conductors, and \( 2a=2.0 \text{m} \) means side length of rectangular, applied voltage between the inner and outer conductors is \( u_0=100 \text{ V} \).

![Fig. 5. Transmission line consisting of rectangular and circular conductors.](image)
The boundary of inner conductor would be evenly subdivided for the 246 nets by the QFEM, the boundary of outer conductor would be subdivided for the 148 linear segments, then the results of characteristic impedance of circular-rectangular transmission line by the mixed method (Quadric FE-BEM) comparison literature [24, 18, 26] and as illustrated in Table 1.

### Table 1. Characteristic impedance of circular-rectangular transmission line (unit: V/m).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>101.02</td>
<td>99.40</td>
<td>101.18</td>
</tr>
<tr>
<td>0.3</td>
<td>76.56</td>
<td>76.30</td>
<td>76.84</td>
</tr>
<tr>
<td>0.4</td>
<td>59.36</td>
<td>59.35</td>
<td>59.56</td>
</tr>
<tr>
<td>0.5</td>
<td>45.75</td>
<td>46.07</td>
<td>46.16</td>
</tr>
<tr>
<td>0.6</td>
<td>35.06</td>
<td>35.16</td>
<td>32.20</td>
</tr>
<tr>
<td>0.7</td>
<td>25.85</td>
<td>25.88</td>
<td>25.89</td>
</tr>
<tr>
<td>0.8</td>
<td>17.65</td>
<td>17.72</td>
<td>17.71</td>
</tr>
<tr>
<td>0.9</td>
<td>10.13</td>
<td>10.19</td>
<td>10.15</td>
</tr>
</tbody>
</table>

See Table 1, the calculation results are well in agreement with that of the previous published data. Therefore, the mixed method precision was quite high.

The shielded deformed coaxial cable [16] as shown in Fig. 6, the cables easily lead to deformed in practice, when placed on the ground for long times due to gravity and the friction between the surface. The parameters: $R_1=0.455$ mm, $R_2=1.49$ mm, $\varepsilon_r=2.03$, $\mu_r=1$. By the general program of the mixed method, the following calculation results of shielded deformed coaxial cable about capacitor were obtained, as illustrated in Table 2.

### Table 2. Comparison of the calculation results of the shielded deformed coaxial cable with the other methods (pF).

<table>
<thead>
<tr>
<th>$h$/mm</th>
<th>Paper C LBEM [12]</th>
<th>CMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>269.3</td>
<td>269.9</td>
</tr>
<tr>
<td>0.6</td>
<td>164.7</td>
<td>164.0</td>
</tr>
<tr>
<td>0.7</td>
<td>134.2</td>
<td>134.2</td>
</tr>
<tr>
<td>0.8</td>
<td>119.6</td>
<td>119.5</td>
</tr>
<tr>
<td>0.9</td>
<td>110.6</td>
<td>110.8</td>
</tr>
<tr>
<td>1.0</td>
<td>105.1</td>
<td>105.1</td>
</tr>
<tr>
<td>1.1</td>
<td>101.2</td>
<td>101.2</td>
</tr>
<tr>
<td>1.2</td>
<td>98.55</td>
<td>98.55</td>
</tr>
<tr>
<td>1.3</td>
<td>96.77</td>
<td>96.78</td>
</tr>
<tr>
<td>1.4</td>
<td>95.59</td>
<td>95.64</td>
</tr>
<tr>
<td>1.45</td>
<td>95.53</td>
<td>95.31</td>
</tr>
</tbody>
</table>

### 4.2. Slots Communication Cable Coupling Capacitance Calculation

As shown in Fig. 7, the communication shielded two-core was consisted of 2 cylindrical conductors and shielded conductor number*section (mm$^2$)=2*0.322 mm$^2$; outer diameter $R=1.86$ mm, space between 2 cores $2a=2*0.64$ mm; $d$ is the slot depth of shield layer, $2s$ is slot width; the retained layer is between the shielded layer and conductors (consisting of laminated steel plastic strip), with the dielectric constant $\varepsilon_r=2.33$. By using the Quadric FE-BEM universal procedure calculation, the influences of different slot shapes (trapezoidal slot, rectangular slot, taper slot) on shielding effectiveness were analyzed.

As shown in Table 2, the calculation results of shielded deformed coaxial cable about capacitor were well in agreement with the linear boundary method and multi-pole theory value [12], and the capacitor increased with the deformation degree of the shielded deformed coaxial cable.

As shown in Fig. 8, for the shielded communication cable, the capacitor of different slots in shielded two-core cable varied with the slot depth $d$ of shielded shell by applying the mixed method with Matlab were given.
The analysis on the shielded effectiveness of communication two-core cable with different slot shapes showed that the internal electromagnetic coupling interference ability was close related with the slot shapes in deep layer, not shallow layer. The coupling capacitance decreased greatly with the slot depth $d$ increase, and the coupling capacitance of trapezoidal slot shielded communication cable changed the biggest, followed by the rectangular slot, and the taper slot was the smallest. When the coupling capacitance changed greatly, the characteristic impedance of transmission line would change, and so was the dispersion, which would have great influence on the transmission quality of cable communication.

5. Conclusions

The boundary element equation of linear segment was discrete from linear interpolating approximation, which was applied to deal with the problem of 2-dimensional electrostatic field, such as two dimension multi-boundary conditions and shielded deformed coaxial transmission lines, and it shows this method is effective and feasible through numerical examples. This method not only solves the discontinuous problem, but also the precision of the method was high. For the overhead shield coaxial cable of ring seam and the overhead shield two-core cable of ring seam that not had been published, this paper provides coupling capacitor of these cable by this method for the first time. It had been shown that this method is provided with a great deal of merits such as simple operation and convenient calculation, so it would be have fine general availability.

1) This paper proposed to use the mixed method (Quadric FE-BEM) to deal with the capacitor of different slots which was set in shielded shell by applying the mixed method with Matlab, such as concealed shield coaxial cable, concealed shield two-core cable.

2) The slot shape had become one of the main causes for reduction the cable shielded effectiveness. The analysis on the shielded effectiveness of communication cables showed that the coupling capacitance of shielded two-core cable of different slots varied scarcely if the slot was in shallow layer, the coupling capacitance changed greatly when the slot depth was greater than 0.5 mm; and the change of coupling capacitance was related with the slot in deep layer of shielded two-core cable at the location of parallel core distance.

The change tendency of coupling capacitance with the different slot shapes at the vertical core distance was almost the same. And, the coupling capacitance of trapezoidal slot shielded communication cable changed the biggest, followed by the rectangular slot, and the taper slot was the smallest.

3) Therefore, the electrical workers should use the taper shape slot in shielded cable slot designs.
4) The coupling effect of any one multi-core cable and different sections cable would be analyzed by the mixed method.

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