Chapter 6

MEASUREMENT OF DIELECTRIC CONSTANT USING WAVEGUIDE DISCONTINUITY
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6.1 INTRODUCTION

Finite element method can be used in analyzing waveguide discontinuities.


This chapter deals with the analysis of discontinuity due to dielectric loaded rectangular waveguide. The evaluation of dielectric constant with variation of $H_y$ component is possible with newly suggested method based on finite element is the main objective of this chapter.
6.2 STATEMENT OF PROBLEM: -

Consider a rectangular waveguide with its axis along Z-direction. The cross section of the waveguide is rectangle with width \( w \) and height \( h \). The waveguide has its two cross sections at \( Z = Z_1 \) and \( Z = Z_2 \). A dielectric of thickness \( t \) occupies the waveguide and is extended from the axis to the waveguide wall. This introduces discontinuity in the rectangular waveguide as shown in figure 6.1. The time harmonic electric field and magnetic field inside waveguides satisfies Maxwell's equations, these equations are given by

\[
\nabla \times \vec{E} = - j \omega \mu_0 \vec{H} \\
\nabla \times \vec{H} = - j \omega \varepsilon_0 \vec{E}
\]

(6.2.1)

(6.2.2)

where \( \omega \) is angular frequency, \( \varepsilon_0 \) and \( \mu_0 \) are the permittivity and the permeability in vacuum and \( \varepsilon \) is the relative permittivity.

Substituting (6.2.2) into (6.2.1), we get

\[
\nabla \times \left[ \varepsilon^{-1} \nabla \times \vec{H} \right] - \kappa_0^2 \vec{H} = 0
\]

(6.2.3)

where

\[
\kappa_0^2 = \omega^2 \varepsilon_0 \mu_0
\]

The magnetic field must satisfy the following boundary conditions.

\[
\vec{H} \cdot \vec{n} = 0, \quad \text{On Conducting walls}
\]

\[
\vec{H} \cdot \vec{n} = \vec{H}_s, \quad \text{On excitation planes.}
\]

Thus by solving of equation (6.2.3) subjected to boundary conditions we can obtained \( H \) - field values at \( Z = Z_1 \) and \( Z = Z_2 \) surfaces. These can be further used to find dielectric constant.
Rectangular waveguide

Rectangular Waveguide with discontinuity

FIGURE 6.1
6.3 FINITE ELEMENT METHOD: -

We consider a waveguide loaded with dielectric as shown in figure 6.2. Here the boundary plane $\Gamma_1$ connect the discontinuity region $\Omega$ of the rectangular waveguide and the region $\Omega$ surrounded by $\Gamma_1$, $\Gamma_2$ and the perfectly conducting wall $\Gamma_0$ encloses the waveguide discontinuities completely.

The problem defined by (6.2.3) may be formulated variationally, and the functional $\Pi$ is expressed as;

$$
\Pi = \iiint_{\Omega} \left( \nabla \times \vec{H} \right)^* \cdot \left( \epsilon^{-1} \nabla \times \vec{H} \right) \, d\Omega - K_0^2 \iiint_{\Omega} \vec{H}^* \vec{H} \, d\Omega \quad (6.3.1)
$$

where $\vec{H}^*$ is the complex conjugate of $\vec{H}$, $\iiint_{\Omega} d\Omega$ is the volume integral in the region $\Omega$.

Now the region $\Omega$ is divided in to hexahedron elements. The magnetic field $\vec{H}_r$ ($r = X, Y, Z$) in each element is approximated by linear polynomials and it is calculated at any point in an element by

$$
\vec{H}_r = \{M\}^T \{H_r\}_e \quad (6.3.2)
$$

Where $\{M\}$ is the shape function vector and $\{H_r\}_e$ is the nodal magnetic field vector in each element. When finite element method is applied to (6.3.2), following matrix equation is obtained.

$$
[S] \{H\} - K_0^2 [T]\{H\} = 0 \quad (6.3.3)
$$

where $\{H\}$ is nodal magnetic field vector in the whole region $\Omega$, $[S]$ and $[T]$ are the matrices related to the first and second terms on right hand side of (6.3.1) respectively. The matrix $[M]$ is given by.

$$
[M] = \begin{bmatrix}
\{M\} & \{0\} & \{0\} \\
\{0\} & \{M\} & \{0\} \\
\{0\} & \{0\} & \{M\}
\end{bmatrix} \quad (6.3.4)
$$

where $\{0\}$ is null vector.

Let nodal magnetic field vector related to the nodes on the boundaries $\Gamma_1$ and $\Gamma_2$ be $\{H\}_1$ and $\{H\}_2$ respectively. Also, let the nodal magnetic field vector
obtained by removing \( \{H\}_1 \) and \( \{H\}_2 \) from the nodal magnetic field vector \( \{H\} \) be \( \{H\}_0 \). Then equation (6.3.4) is rewritten as follows;

\[
\begin{bmatrix}
[R]_{11} & [R]_{10} & [R]_{12} \\
[R]_{01} & [R]_{00} & [R]_{02} \\
[R]_{21} & [R]_{20} & [R]_{22}
\end{bmatrix}
\begin{bmatrix}
\{H\}_1 \\
\{H\}_0 \\
\{H\}_2
\end{bmatrix} = 0
\]

(6.3.5)

where \([R]_{11}, [R]_{10}, \ldots, [R]_{22}\) are the sub matrices of the matrix \([R]\);

\[
[R] = [S] - K_0^2 [T]
\]

(6.3.6)

---

**FIGURE 6.2 RECTANGULAR WAVEGUIDE LOADED WITH DIELECTRIC**
BOUNDARY MARCHING AND SUBSTRUCTURING

The surface terms in equation (6.3.6) are neglected assuming the continuity at the surfaces \( \Gamma_1 \) and \( \Gamma_2 \). For a piece of waveguide of small finite length this does not hold. To make its validity we apply the boundary marching technique. Hence we consider that the geometrical structure of the problem consist of three regions.

- A small section of rectangular waveguide from the input side, which can be extended to infinity.
- Small piece of rectangular waveguide containing discontinuity.
- Another small section of rectangular waveguide from output side, which can be extended to infinity.

The waveguide sections on input and output sides are treated by boundary marching technique in which length of the waveguide is considered to be finite, small and it is doubled every time to make it very large in few steps of doubling. The discontinuity region is divided into few sections taking care that the discontinuity occupies complete section and not a partial section. Firstly the FEM system matrices are developed for the first section of the waveguide piece containing discontinuity. Then second section FEM system matrices are worked out. Eliminating the unknowns on the common surface of the two sections, using static condensation method combines the two-section system matrices. This amounts to considering two sections as one big section. The section FEM system matrices are then found and combine with the earlier system matrix for two sections. Again the condensation method is used to eliminate the common surface unknowns.

If there are \( N \) numbers of unknowns on one cross-sectional surface of the waveguide then system matrices for the infinitely long input side waveguide will be \((2N \times 2N)\) and so will be the, size of system matrices for discontinuity region waveguide and infinitely long waveguide on output side. By combining these matrices we get a system matrices of the size \((2N \times 2N)\). These matrices will be for unknowns for only four surfaces i.e. first surface of infinitely long input section, first and second surface of discontinuity section and end point surface of output
section. Using the field values at input and output ends we can solve the matrix equation and can find field values at the first and second surface of discontinuity region waveguide.

6.4 BOUNDARY- MARCHING METHOD: -

The steps of boundary-marching process are shown in figure 6.3. The far field and near field planes are initially placed at the same location, then far field plane is moved away step by step with the distance at each step growing larger as the far field recedes. To develop the computational algorithm, let $S_1$ and $S_2$ be the two surfaces enclosing the input side waveguide segment. As waveguide is uniform, $S_1$ and $S_2$ are congruent. The waveguide segment is discretised into finite elements such that the finite element nodes and edges must leave $S_1$ and $S_2$ congruent and there is only one element along thickness of waveguide. On discretisation of the segment into number of finite elements and minimizing the corresponding magnetic field functional, the following equation is obtained.

$$
\begin{bmatrix}
[P]^{0}_{11} & [P]^{0}_{12} \\
[P]^{0}_{21} & [P]^{0}_{22}
\end{bmatrix}
\begin{bmatrix}
[H]^{0}_{1} \\
[H]^{0}_{2}
\end{bmatrix} = \{0\} \quad (6.4.1)
$$

The matrix equation had been partitioned so that the sub-matrices identified by subscript 1 correspond to finite element nodes located on plane $S_1$. Those identified by subscript 2 correspond to finite element nodes located on plane $S_2$. Thus $[H]_1$ represents the nodal magnetic fields on boundary surface $S_1$, $[H]_2$ represents the nodal magnetic fields on boundary plane $S_2$.

The coefficient matrix of magnetic field equation describes the interrelationship of magnetic field components at the two ends of a fixed length of initial piece of uniform waveguide. A section of waveguide twice that length can therefore be molded without loss of accuracy by cascading two such matrices. Combining two identical segments and enforcing the field continuity on their common boundary thus obtained the description of a double length segment of waveguide.
\[
\begin{bmatrix}
[p]_{11}^0 & [p]_{12}^0 & 0 \\
[p]_{21}^0 & [p]_{11}^0 + [p]_{22}^0 & [p]_{22}^0 \\
0 & [p]_{21}^0 & [p]_{22}^0
\end{bmatrix}
\begin{bmatrix}
[H]_{11}^0 \\
[H]_{12}^0 \\
[H]_{22}^0
\end{bmatrix} = \{0\}
\]
(6.4.2)

One may consider surface \(S_2\) as internal surface and \(S_3\) as a new \(S_2\) surface. Hence above equation can be expressed as;

\[
\begin{bmatrix}
[p]_{11}^0 & [p]_{11}^0 & [p]_{12}^0 \\
[p]_{11}^0 & [p]_{11}^0 & [p]_{12}^0 \\
[p]_{21}^0 & [p]_{21}^0 & [p]_{22}^0
\end{bmatrix}
\begin{bmatrix}
[H]_{11}^0 \\
[H]_{12}^0 \\
[H]_{22}^0
\end{bmatrix} = \{0\}
\]
(6.4.3)

The magnetic field values at internal nodes is of no interest; they can be eliminated removing \([H]_{11}^0\) with the process of static condensation. This way we get super element twice as long as the original one:

\[
\begin{bmatrix}
[p]_{11}^1 & [p]_{12}^1 \\
[p]_{21}^1 & [p]_{22}^1
\end{bmatrix}
\begin{bmatrix}
[H]_{11}^1 \\
[H]_{12}^1
\end{bmatrix} = \{0\}
\]
(6.4.4)

where the superscript 1 indicates that one doubling of the waveguide length has taken place. Note that \([H]_{21}^1\) are field values at new \(S_2\) or old \(S_3\) planes. The four new sub matrices are obtained as;

\[
[p]_{11}^1 = [p]_{11}^0 - [p]_{11}^0 \left([p]_{ii}^0 \right)^{-1} [p]_{11}^0
\]
(6.4.5)

\[
[p]_{12}^1 = -[p]_{11}^0 \left([p]_{ii}^0 \right)^{-1} [p]_{12}^0
\]
(6.4.6)

\[
[p]_{21}^1 = -[p]_{2i}^0 \left([p]_{ii}^0 \right)^{-1} [p]_{11}^0
\]
(6.4.7)
\[ [P]_{21}^{k+1} = [P]_{21}^0 - [P]_{2i}^0 \left( [P]_{ii}^0 \right)^{-1} [P]_{i2}^0 \]  

(6.4.8)

The new super element representing the waveguide section is twice long. Further lengthening of the waveguide segment is achieved by applying the same procedure recursively. After \( k \) recursions, the matrix relating the field distribution at surface 1 to the excitation field on the far plane can be expressed in terms of the sub matrices of previous recursion as follows;

\[ [P]_{11}^{k+1} = [P]_{11}^k - [P]_{1i}^k \left( [P]_{ii}^k \right)^{-1} [P]_{i1}^k \]  

(6.4.9)

\[ [P]_{12}^{k+1} = -[P]_{1i}^k \left( [P]_{ii}^k \right)^{-1} [P]_{i2}^k \]  

(6.4.10)

\[ [P]_{21}^{k+1} = -[P]_{2i}^k \left( [P]_{ii}^k \right)^{-1} [P]_{i1}^k \]  

(6.4.11)

\[ [P]_{22}^{k+1} = [P]_{22}^k - [P]_{2i}^k \left( [P]_{ii}^k \right)^{-1} [P]_{i2}^k \]  

(6.4.12)

At each recursion step, the length of the super element is augmented by a factor of 2. Consequently, in the course of \( N \) recursions, the length of the uniform waveguide in the propagation direction grows by a factor of \( 2^N \). In effect the procedure is equivalent to marching out the boundary of the uniform waveguide from the plan \( S_1 \) to the far plane. The method therefore provides a simple way for simulation and investigation of wave propagation in any arbitrary shaped waveguide.
6.5 SUBTRACTING AND CONDENSATION

By using surfaces perpendicular to the axis of waveguide the region \( \Omega \) is divided into number of sub regions. Applying finite element method to first sub region, the following equation is obtained.

\[
\begin{bmatrix}
[w^{(1)}_{11}] & [w^{(1)}_{12}]
\end{bmatrix}
\begin{bmatrix}
[H^{(1)}_{11}]
\end{bmatrix}
= \{0\} \tag{6.5.1}
\]

Similarly for second sub region we can write

\[
\begin{bmatrix}
[w^{(2)}_{11}] & [w^{(2)}_{12}]
\end{bmatrix}
\begin{bmatrix}
[H^{(2)}_{11}]
\end{bmatrix}
= \{0\} \tag{6.5.2}
\]

The continuity condition of the magnetic field \( \vec{H} \) at the interface \( S^1 \) and \( S^2 \)

Between first and second sub regions is

\[
\{H^{(1)}_{2}\} = \{H^{(2)}_{1}\} \tag{6.5.3}
\]

Using (6.5.3), we may combine (6.5.1) with (6.5.2) and obtain the following equation:

\[
\begin{bmatrix}
[w^{(1)}_{11}] & [w^{(1)}_{12}]
\end{bmatrix}
\begin{bmatrix}
[H^{(1)}_{11}]
\end{bmatrix}
= \{0\} \tag{6.5.4}
\]

where \( \{0\} \) is a null matrix.

Eliminating \( \{H^{(1)}_{2}\} = \{H^{(2)}_{1}\} \) from equation (6.5.4), we get
\[
\begin{bmatrix}
[R]^{(12)}_{11} & [R]^{(12)}_{12} \\
[R]^{(12)}_{21} & [R]^{(12)}_{22}
\end{bmatrix}
\begin{bmatrix}
[H]^{(1)}_1 \\
[H]^{(2)}_2
\end{bmatrix}
= \{0\}
\]
(6.5.5)

where

\[
[R]^{(12)}_{11} = [w]^{(1)}_{11} - [w]^{(1)}_{12} \left([w]^{(1)}_{22} + [w]^{(2)}_{11}\right)^{-1} [w]^{(1)}_{21}
\]
(6.5.6)

\[
[R]^{(12)}_{12} = -[w]^{(1)}_{12} \left([w]^{(1)}_{22} + [w]^{(2)}_{11}\right)^{-1} [w]^{(2)}_{12}
\]
(6.5.7)

\[
[R]^{(12)}_{21} = -[w]^{(2)}_{21} \left([w]^{(1)}_{12} + [w]^{(2)}_{11}\right)^{-1} [w]^{(1)}_{21}
\]
(6.5.8)

\[
[R]^{(12)}_{22} = [w]^{(12)}_{22} - [w]^{(2)}_{21} \left([w]^{(1)}_{12} + [w]^{(2)}_{11}\right)^{-1} [w]^{(2)}_{12}
\]
(6.5.9)

where superscript\((12)\) indicates that the quantities relate to the sub region 1 to sub region 2. Combining the further sub regions in the same way, one arrives to the relation at the end of \(n^{th}\) sub region combination as;

\[
\begin{bmatrix}
[R]^{(1n)}_{11} & [R]^{(1n)}_{12} \\
[R]^{(1n)}_{21} & [R]^{(1n)}_{22}
\end{bmatrix}
\begin{bmatrix}
[H]^{(1)}_1 \\
[H]^{(2)}_2
\end{bmatrix}
= \{0\}
\]
(6.6.10)

where the superscript\((1n)\) indicates that the quantities relate to the sub region 1 to sub region \(n\).

6.6 PROCEDURE USED

- Consider a sample holding waveguide piece of 6-block as shown in figure 6.3. Let thickness of each block be 2mm i.e. \(\lambda/16\), where \(\lambda = 3.2\text{cm}\).

- For the first block of single element thickness developed the matrix \([W \ W]\). Apply the boundary conditions at points on the metal
surface and modify the matrix [W W]. Now split the matrix [W W] into four sub matrices i.e. $P_{11}$, $P_{12}$, $P_{21}$, $P_{22}$ by portioning [W W] suitably such that matrix $[P_{ij}]$ relates fields at $i^{th}$ surface points to field at $j^{th}$ surface points.

- Apply the boundary marching process, described above, at least 10 times and establish matrices $P_{11}$, $P_{12}$, $P_{21}$, $P_{22}$ that will relating the fields at the two ends of the waveguide $2^{10}$ times long.

$$
\begin{bmatrix}
P_{11} & P_{12} \\
P_{21} & P_{22}
\end{bmatrix}
\begin{bmatrix}
H_1 \\
H_2
\end{bmatrix}
= 0
$$

(6.6.1)

- Calculating the input H-field components for $TE_{10}$ mode with assumed amplitude and phase and then assuming these field values at the far plane one obtains the field expressions at surface $S_1$ due to incident field.

$$
\begin{bmatrix}
P_{12} \\
P_{22}
\end{bmatrix}
\{H_2\}
= -\begin{bmatrix}
P_{11} \\
P_{21}
\end{bmatrix}
\{H_1\}
= \begin{bmatrix}
C_1 \\
C_2
\end{bmatrix}
$$

(6.6.2)

Where $\{H_1\}$ is known.

- The arrived matrices are stored as

$$
[R_{11}] = [P_{12}], \quad [R_{21}] = [P_{22}].
$$

(6.6.3)

$$
[C_1] = -[P_{12}] \{H_1\}, \quad [C_1] = -[P_{21}] \{H_1\}.
$$

- The block number 8 is considered to be of the thickness $(\lambda / 16)$. This is to be elongated to the length of size $\lambda$, with initial length of $(\lambda / 16)$. The matrix $[W W]$ is set and applying boundary condition at metal surface points modifies it, the matrix $[W W]$ is partitioned in $P_{11}$, $P_{12}$, $P_{21}$, and $P_{22}$ matrices and the field relation is expressed as
\[
\begin{bmatrix}
P_{11} & P_{12} \\
P_{21} & P_{22}
\end{bmatrix}
\begin{bmatrix}
H_8 \\
H_9
\end{bmatrix} = \{0\}
\]

(6.6.4)

- Now the boundary marching is applied four times so that the length of the piece becomes \(2^4 = 16\) times of initial length \((\lambda / 16)\). Since the length of the output sidepiece is \(\lambda\) the field values at its two cross-sectional end faces will be same i.e.

\[
\{H_8\} = \{H_9\}
\]

(6.6.5)

Thus

\[
\begin{bmatrix}
P_{11} + P_{12} \\
P_{21} + P_{22}
\end{bmatrix}
\begin{bmatrix}
H_8 \\
H_9
\end{bmatrix} = \{0\}
\]

(6.6.6)

- The arrived matrices are stored in the form of R matrices as

\[
\begin{bmatrix}
R_{12}
\end{bmatrix} = [P_{11}] + [P_{12}]
\]

(6.6.7)

\[
\begin{bmatrix}
R_{22}
\end{bmatrix} = [P_{21}] + [P_{22}]
\]

- The test waveguide piece containing material discontinuity is divided into 6-sections and one section contains the dielectric material. To develop two surface field relations for this section we follow the following algorithm.

- Calculate \(W \ W\) for \(K^{th}\) block. (\(K=2\))
- Apply the waveguide surface boundary conditions.
- Split \(W \ W\) in to \(P_{11}, P_{12}, P_{21}\) and \(P_{22}\).
- Calculate \(ww\) for \((K+1)^{th}\) block.
- Apply the waveguide surface boundary conditions.
- Split \(ww\) in to \(Q_{11}, Q_{12}, Q_{21}\) and \(Q_{22}\).
- If \(K < 8\) then go back.
- The matrices for the input end section and output end section are stored in \([R]\) matrices. The constants corresponding to the input fields are stored in \([C]\) submatrices whereas the matrices corresponding to the test waveguide part are stored in \([P]\)
submatrices. Combining all these matrices one can establish a matrix relation

\[ [A A] \{ X \} = \{ B B \}. \]

- Where

\[ [A A_{11}] = [P_{11}] + [R_{11}] \]
\[ [A A_{12}] = [P_{12}] + [R_{12}] \]
\[ [A A_{21}] = [P_{21}] + [R_{21}] \]
\[ [A A_{22}] = [P_{22}] + [R_{22}] \]
\[ \{ B B_1 \} = \{ C_1 \} \]
\[ \{ B B_2 \} = \{ C_2 \} \]
\[ [AA] \{ X \} = \{ BB \}, \quad \{ X \} \text{ being H Field components at } S_1 \text{ and } S_8 \text{ cross-section faces.} \]

- The matrix equation is an equation with complex coefficients. Solving it we can get the H- field components. Varying the \( \varepsilon \) of discontinuity material and evaluating the H- field components we can establish a relation between \( H_y \) field component at one point on surface \( S_8 \) and \( \varepsilon \) of the material.
FIGURE 6.3: GEOMETRY FOR BOUNDARY MARCHING AND SUBSTRUCTURING
6.7 NUMERICAL CALCULATION:-

A Rectangular waveguide piece with cross-sectional dimensions $a = 2.4$cm and $b = 1.2$cm and length 1.2cm is supposed to contain discontinuity of 2 mm thickness. This structure is divided initially into six rectangular blocks as shown in figure 6.3. Then each block is divided in to number of hexahedron elements. Total number of nodes on each cross sectional rectangular surface is 30. At each nodal point there are three unknowns, so total number of unknowns on each surface will be $30 \times 3 = 90$.

The total number of unknowns on four surfaces i.e. first surface of infinitely long input section, first and second surface of discontinuity section and end point surface of output section are $90 \times 4 = 360$. Thus matrix order to be solved for the system is $(360 \times 360)$.

The field components at the second port of the test guide, with input microwave power at first port, are worked out with different samples placed in the test guide. These evaluated field component values are shown in table 6.1 and the variations are plotted in fig. 6.4. This serves as a calibration curve for dielectric measurement.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Dielectric Constant</th>
<th>Hy -Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>0.4815</td>
</tr>
<tr>
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<td>2</td>
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</tr>
<tr>
<td>4</td>
<td>2.5</td>
<td>0.9981</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>1.1550</td>
</tr>
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<td>6</td>
<td>3.5</td>
<td>1.2860</td>
</tr>
<tr>
<td>7</td>
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</tr>
<tr>
<td>8</td>
<td>4.5</td>
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</tr>
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</tr>
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<td>16</td>
<td>8.5</td>
<td>2.3740</td>
</tr>
</tbody>
</table>
6.8 CONCLUSIONS: -

A new finite element approach is developed and applied to analyze waveguide discontinuities. This approach uses boundary marching and sub structuring method to keep the size of matrices small. The values of $H_y$ components calculated by this technique with the dielectric material and without dielectric material provide us a calibration curve for $H_y$ with the variation of dielectric constant $\varepsilon$. This gives rise to a method of measurement of $\varepsilon$ in terms of $H_y$ component.
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