1.0
0.8
0.6
0.4
0.2
0

Fig. 3. Expanded view of the peaks of the magnitudes of the locating vectors for the balls measured versus distance. The shift of the peaks toward the source for large balls is easily seen.

Fig. 4. Computed positions of the peak of the radar-echo, and arg(\Gamma(t)) versus ball diameter. It is seen that small balls appear to be farther away than their centers. Echoes of large balls move closer to the source. As a cross-check, the points indicated by X were computed using the first and last frequencies only.

susceptance in the center. Since the guide wavelength in the tapered section lengthens, the shunt susceptance appears to be farther away (group-delay is increased). For very large balls, this taper is very severe (guides tending toward cutoff), and dominates over the effect of the shunt susceptance and thus puts the reflection forward.

The experimental uncertainty in the echo locations is difficult to state, but repeated measurements produced very similar results. The individual departures of the points on Fig. 4 from the smooth fitted curve give an indication of the scatter. As a cross-check, the point corresponding to the largest, seemingly anomalous, echo location was computed using only the two extreme frequencies of the set of eleven, and reproduced the trend of the results of the full set, as shown in Fig. 4.

In Fig. 4, the computed phase of the locating vector is shown at the echo-maxima. For small balls, the phase tends toward –90°, meaning that small balls may be regarded as lumped capacitive obstacles, whereas large balls exhibit phases which approach 180°, the expected value for an impedance which approaches a short circuit.

The Smith-chart plot of the complex locating vector (Fig. 5) indicates a quasi-capacitive behavior for all ball sizes. The departure from purely capacitive loading is attributed to the breakdown of the lumped element approximation as the balls become larger and the impedance is distributed along the waveguide.

REFERENCES


Propagation on a Sheath Helix in a Coaxially Layered Lossy Dielectric Medium

MARK J. HAGMANN, MEMBER, IEEE

Abstract — Radial and axial dependence of the azimuthally symmetric fields in each coaxial layer may be expressed in terms of modified Bessel Manuscript received April 26, 1982; revised August 3, 1983.
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functions and complex exponentials, respectively. There are two unknown coefficients in expressions for the innermost and outermost layers, and four in each of the other layers. Equations derived from boundary conditions are cascaded so that coefficients in the two layers adjacent to the helix are obtained as linear functions of coefficients in the innermost and outermost layers. Application of boundary conditions at the sheath helix results in an error term allowing an iterative solution for the complex axial propagation constant. An example of an inhomogeneous bone/muscle/fat/skin model of the human upper arm is used to test suitability of the helical coil in hyperthermia for the treatment of cancer. Deep, relatively uniform, deposition of energy may be obtained.

I. INTRODUCTION

The helical coil, in addition to its use in the traveling-wave tube (TWT) [1], has been considered for many other applications, including drying continuous filaments by microwave heating [2] and hyperthermia for the treatment of cancer [3]. It is necessary to modify the original treatment by Sensiper [4] to include regions having different dielectric properties in order to improve the realism of modeling in some of these applications. In particular, the skin-fat-muscle dielectric layering has been shown to alter the coupling of electromagnetic energy to the human body [5], so such layering must be considered when modeling systems for use in hyperthermia.

Several methods have been used to correct for the presence of different dielectrics. An approximation valid at high frequencies has been used to simplify the analytical solution for a helix having either coaxial dielectric layers [6] or wedge-shaped dielectric supports that are spaced periodically in the angular coordinate about the helix axis [7]. Equivalent circuit parameters have also been obtained to approximate dispersion characteristics of a helix perturbed by the presence of various dielectric and metallic objects [8], [9]. In evaluation of the helical coil as an applicator for use in hyperthermia, solutions are required for the local field values over a wide range of frequencies. None of the methods just described are suitable. A new method having high numerical efficiency is presented in this paper.

No rigorous solution has yet been found for a helix having realistic round wire. All work presented in this paper is for the realistic round wire. All work presented in this paper is for the helix having either coaxial dielectric layers [6] or wedge-shaped dielectric supports that are spaced periodically in the angular coordinate about the helix axis [7]. Equivalent circuit parameters have also been used to obtain the approximate dispersion characteristics of a helix perturbed by the presence of various dielectric and metallic objects [8], [9]. In evaluation of the helical coil as an applicator for use in hyperthermia, solutions are required for the local field values over a wide range of frequencies. None of the methods just described are considered suitable. A new method having high numerical efficiency is presented in this paper.

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\[ D_{i+1} = \begin{bmatrix} B_i \left[ I_0(\tau_{i+1} r_i) I_1(\tau_{i+1} r_i) - \frac{\rho_{i+1} \tau_{i+1}}{\rho_{i+1} \tau_{i+1}} I_1(\tau_{i+1} r_i) I_0(\tau_{i+1} r_i) \right] \\
+ D_i \left[ K_0(\tau_{i+1} r_i) I_1(\tau_{i+1} r_i) + \frac{\rho_{i+1} \tau_{i+1}}{\rho_{i+1} \tau_{i+1}} K_1(\tau_{i+1} r_i) I_0(\tau_{i+1} r_i) \right] \end{bmatrix} \quad (11) \]

Alternatively, the following equations may be obtained for downward recursion in the coefficients where, again, \( r_i \) must not be the boundary at the sheath helix:

\[ A_i = \begin{bmatrix} A_{i-1} \left[ I_0(\tau_{i+1} r_i) K_1(\tau_{i+1} r_i) + \frac{\rho_{i-1} \tau_{i+1}}{\rho_{i-1} \tau_{i+1}} I_1(\tau_{i+1} r_i) K_0(\tau_{i+1} r_i) \right] \\
+ C_{i-1} \left[ K_0(\tau_{i+1} r_i) K_1(\tau_{i+1} r_i) - \frac{\rho_{i-1} \tau_{i+1}}{\rho_{i-1} \tau_{i+1}} K_1(\tau_{i+1} r_i) K_0(\tau_{i+1} r_i) \right] \end{bmatrix} \quad (12) \]

\[ C_i = \begin{bmatrix} A_{i-1} \left[ I_0(\tau_{i+1} r_i) I_1(\tau_{i+1} r_i) - \frac{\rho_{i-1} \tau_{i+1}}{\rho_{i-1} \tau_{i+1}} I_1(\tau_{i+1} r_i) I_0(\tau_{i+1} r_i) \right] \\
+ C_{i-1} \left[ K_0(\tau_{i+1} r_i) I_1(\tau_{i+1} r_i) + \frac{\rho_{i-1} \tau_{i+1}}{\rho_{i-1} \tau_{i+1}} K_1(\tau_{i+1} r_i) I_0(\tau_{i+1} r_i) \right] \end{bmatrix} \quad (13) \]

\[ B_i = \begin{bmatrix} B_{i-1} \left[ I_0(\tau_{i+1} r_i) K_1(\tau_{i+1} r_i) + \frac{\rho_{i-1} \tau_{i+1}}{\rho_{i-1} \tau_{i+1}} I_1(\tau_{i+1} r_i) K_0(\tau_{i+1} r_i) \right] \\
+ D_{i-1} \left[ K_0(\tau_{i+1} r_i) K_1(\tau_{i+1} r_i) - \frac{\rho_{i-1} \tau_{i+1}}{\rho_{i-1} \tau_{i+1}} K_1(\tau_{i+1} r_i) K_0(\tau_{i+1} r_i) \right] \end{bmatrix} \quad (14) \]

\[ D_i = \begin{bmatrix} B_{i-1} \left[ I_0(\tau_{i+1} r_i) I_1(\tau_{i+1} r_i) - \frac{\rho_{i-1} \tau_{i+1}}{\rho_{i-1} \tau_{i+1}} I_1(\tau_{i+1} r_i) I_0(\tau_{i+1} r_i) \right] \\
+ D_{i-1} \left[ K_0(\tau_{i+1} r_i) I_1(\tau_{i+1} r_i) + \frac{\rho_{i-1} \tau_{i+1}}{\rho_{i-1} \tau_{i+1}} K_1(\tau_{i+1} r_i) I_0(\tau_{i+1} r_i) \right] \end{bmatrix} \quad (15) \]

Equations (8)—(11) may be written in the following form:

\[ A_{i+1} = G_{i+1}^A A_i + G_{i+1}^C C_i \quad (16) \]

\[ C_{i+1} = G_{i+1}^C A_i + G_{i+1}^C C_i \quad (17) \]

\[ B_{i+1} = G_{i+1}^B B_i + G_{i+1}^D D_i \quad (18) \]

\[ D_{i+1} = G_{i+1}^B B_i + G_{i+1}^D D_i \quad (19) \]

It was noted earlier that we require \( C_1 \) and \( D_1 \) to be identically zero. Then using (16)—(19) with \( i = 1 \) results in the following:

\[ A_2 = G_{i+1}^A A_1 \quad (20) \]

\[ C_2 = G_{i+1}^C A_1 \quad (21) \]

\[ B_2 = G_{i+1}^B B_1 \quad (22) \]

\[ D_2 = G_{i+1}^D B_1 \quad (23) \]

Using (16)—(19) a second time, with \( i = 2 \), and (20)—(23) results in the following:

\[ A_3 = \begin{bmatrix} G_{i+2}^A A_1 + G_{i+2}^C C_1 \end{bmatrix} A_1 \quad (24) \]

\[ C_3 = \begin{bmatrix} G_{i+2}^C A_1 + G_{i+2}^C C_1 \end{bmatrix} A_1 \quad (25) \]

\[ B_3 = \begin{bmatrix} G_{i+2}^B B_1 + G_{i+2}^B B_1 \end{bmatrix} B_1 \quad (26) \]

\[ D_3 = \begin{bmatrix} G_{i+2}^D B_1 + G_{i+2}^D B_1 \end{bmatrix} B_1 \quad (27) \]

Continuing this upward cascaded recursion, it is possible to define four \( \gamma \) coefficients as follows:

\[ A_M = \gamma_{i+1} A_1 \quad (28) \]

\[ C_M = \gamma_{i+1} A_1 \quad (29) \]

\[ B_M = \gamma_{i+1} B_1 \quad (30) \]

\[ D_M = \gamma_{i+1} B_1 \quad (31) \]

where \( M \) is the index of the coaxial dielectric layer just inside the helix.

Equations (12)—(15) may be written in the following form:

\[ A_{i-1} = X_{i-1}^A A_i + X_{i-1}^C C_i \quad (32) \]

\[ C_{i-1} = X_{i-1}^C A_i + X_{i-1}^C C_i \quad (33) \]

\[ B_{i-1} = X_{i-1}^B B_i + X_{i-1}^D D_i \quad (34) \]

\[ D_{i-1} = X_{i-1}^D B_i + X_{i-1}^D D_i \quad (35) \]

It was noted earlier that we require \( A_N \) and \( B_N \) to be identically zero. Then, using (32)—(35), with \( i = N \), results in the following:

\[ A_N = X_N^B C_N \quad (36) \]

\[ C_N = X_N^C C_N \quad (37) \]

\[ B_N = X_N^D D_N \quad (38) \]

\[ D_N = X_N^D D_N \quad (39) \]

Using (32)—(35) a second time, with \( i = N - 1 \), and (36)—(39) results in the following:

\[ A_N = X_{N-1}^A A_i + X_{N-1}^C C_i \quad (40) \]

\[ C_N = X_{N-1}^C A_i + X_{N-1}^C C_i \quad (41) \]

\[ B_N = X_{N-1}^B B_i + X_{N-1}^D D_i \quad (42) \]

\[ D_N = X_{N-1}^D B_i + X_{N-1}^D D_i \quad (43) \]

Continuing this downward cascaded recursion, it is possible to define four \( \xi \) coefficients as follows:

\[ A_{M-1} = \xi_{i-1} A_i \quad (44) \]

\[ C_{M-1} = \xi_{i-1} C_i \quad (45) \]

\[ B_{M-1} = \xi_{i-1} B_i \quad (46) \]

\[ D_{M-1} = \xi_{i-1} D_i \quad (47) \]

At the sheath boundary, \( E_z \) and \( E_z \) must be continuous. Also, the electric field intensity parallel to the winding \( (E_{1z}) \) must vanish and the magnetic field intensity parallel to the winding \( (H_{1z}) \) must be continuous. The fifth condition is that the step in the magnetic field intensity perpendicular to the winding \( (H_{2z}) \) at the sheath boundary must be equal to the sheet current density of...
been presented to date.

phantom models of the human arm and thigh have demonstrated
layers of teflon 3 and 2 mm in thickness, located just inside and
man upper arm was used with the helical coil for numerical
testing. Values for the dielectric properties of the tissues were in
a pitch angle of 30 and a radius of 5.0 cm. The model included
that it is possible to obtain deep, relatively uniform, heating of

It is possible to define the following algorithm for solution.

1) Assume a trial value of $\beta$.
2) Determine the $r_1$ by (7).
3) Use cascaded upward recursion to determine the four $\gamma$.
4) Use cascaded downward recursion to determine the four $\xi$.
5) Use the $\gamma$ and $\xi$ values in the five equations at the helix
boundary to solve for $A_1, B_1, C_N, D_N$.
6) The system is overdetermined, so an error results. If the
error is above tolerance, a correction is made in $\beta$ and return to
Step 2.
7) When the error is sufficiently small, then upward and
downward recursion are used to determine the remaining coeffi-
cients.

The algorithm has the advantage that no approximation other
than the sheath helix model is required. The number of opera-
tions necessary to solve the system is linear in $N$ and is dominated
by evaluation of the $G$ and $X$ terms. Procedures used for numeri-
cal implementation of the algorithm are described in the next
section.

III. NUMERICAL IMPLEMENTATION

An efficient iterative scheme must be used to find the complex
value of $\beta$ such that a complex error term is minimized. Müller's
method was first proposed as an efficient iterative procedure for
finding real and complex roots of a polynomial equation [11]. It
has been used successfully with a variety of more general equa-
tions, but there has been no proof of convergence in the large
[12]. In the present work, an existing algorithm [13] for Müller's
method has been used. The Forsythe procedure [12] of deflation
is incorporated in the algorithm to allow locating multiple com-
plex roots which correspond to different modes of the electro-
magnetic fields. It was necessary to modify the procedure for
selecting step size in order to obtain a universal routine that has
properly converged in all tests made thus far.

IV. EXAMPLES

The helical coil has been considered for use in hyperthermia
for the treatment of cancer [3]. For a wide range of design
parameters, a helical coil in free space will produce an electric
field that is essentially parallel with the coil axis, and relatively
uniform throughout the cross section of the coil [14], [15]. An
incident field with these properties would be expected to produce
relatively uniform deposition in a cylinder of lossy dielectric
contained within the coil. Experiments with cylindrical fat–muscle
phantom models of the human arm and thigh have demonstrated
that it is possible to obtain deep, relatively uniform, heating of
the muscle-equivalent region [3]. No analysis of this problem has
been presented to date.

An inhomogeneous bone/muscle/fat/skin model of the hu-
man upper arm was used with the helical coil for numerical
testing. Values for the dielectric properties of the tissues were in
agreement with those reported by others [16], [17]. The helix had
a pitch angle of 3° and a radius of 5.0 cm. The model included
layers deleted, as well as the cylinder being replaced with homo-
geneous muscle. No evidence of numerical instability or failures
in convergence were found in these tests. Typically, the values of
$\beta$ were found to converge to four-place accuracy in 12 iterations,
and six-place accuracy in 15 iterations. Additional (fictitious)
layers were added by partitioning various layers into two or more
parts having the same dielectric properties, but this caused no
significant change in the results. Two or more roots occur at
frequencies somewhat over 100 MHz, and they appear to corre-
spond to modes having differing radial dependence.

Fig. 1 shows the phase velocity (normalized relative to the
velocity of light in vacuum) as a function of frequency for a sheath helix having a

Fig. 1. Phase velocity as a function of frequency for a sheath helix having a

The procedures described in this paper were used in the
analysis of 1) the model as described in Table I, 2) the model
with the teflon layers deleted, and 3) the model with the teflon
layers deleted, as well as the cylinder being replaced with homo-
geneous muscle. No evidence of numerical instability or failures
in convergence were found in these tests. Typically, the values of
$\beta$ were found to converge to four-place accuracy in 12 iterations,
and six-place accuracy in 15 iterations. Additional (fictitious)
layers were added by partitioning various layers into two or more
parts having the same dielectric properties, but this caused no
significant change in the results. Two or more roots occur at
frequencies somewhat over 100 MHz, and they appear to corre-
spond to modes having differing radial dependence.

Muscle 3.4
Fat 3.9
Skin 4.0
Air 4.7
Teflon 5.2
Air ---

The axial depth was defined as the distance measured parallel to the helix axis for which all fields in
a traveling wave are reduced in amplitude by a factor of $1/e$. The slight decrease of axial depth caused by the teflon would also be
seen with a decrease in helix radius. The axial depth is noticeably
greater for the homogeneous muscle cylinder than for the inho-
mogeneous model.
Fig. 2 Axial depth as a function of frequency for a sheath helix having a lossy dielectric cylinder on its axis.

Fig. 3 Normalized SAR as a function of radius in a lossy dielectric cylinder within a sheath helix at 27.12 MHz.

Fig. 3 shows the specific absorption rate (SAR), normalized to the maximum which occurs at the skin surface, as a function of radius for a frequency of 27.12 MHz. The large decrease in energy deposition within the bone and fat layers is largely due to the decreased conductivity of those dielectrics. The fractional change in normalized SAR is more pronounced at the muscle–bone interface than at the muscle–fat or fat–skin interfaces. This is attributed to the fact that the radial component of the electric field is negligible at the larger radii, so boundary conditions require the magnitude of the electric field to decrease with the decrease in helix radius, which is consistent with the effect of teflon on axial depth.

The deep, relatively uniform, deposition of energy illustrated in Fig. 3 is in qualitative agreement with experimental results obtained using models with a thermographic camera [3] and confirms that the helical coil shows promise for use as an applicator in hyperthermia.

V. CONCLUSION

The numerical method described in this paper has been found to be useful for evaluation of the fields of a sheath helix in a coaxially layered lossy dielectric medium. The examples presented pertain to clinical applications and support experimental results suggesting suitability of the helical coil as an applicator in hyperthermia.

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REFERENCES


Impedance Calculation of Three Narrow Resonant Strips on the Transverse Plane of a Rectangular Waveguide

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Abstract—A theoretical analysis has been developed to calculate the impedance of two inductive strips and one capacitive strip located on the transverse plane of a rectangular waveguide. The current ratios among the strips were determined by a variational method and then used for impedance calculations. The results can be applied to the impedance calculations of a single capacitive strip, two inductive strips, or three inductive strips as special cases.

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