NUMERICAL ANALYSIS OF COIL-LOADED DIPOLE ANTENNA

Akihide SAKITANI  Shigeru EGASHIRA  Taira MATSUNAGA
Faculty of Science and Engineering, SAGA University
Saga, Japan 840

1. Introduction

It is well known that the characteristics of an antenna are improved by loading. For example we can increase the directivity by locating the inductive or capacitive impedances intermittently on an antenna.

The analysis of coil-loaded antenna has been investigated by Harrison(1), Lin(2), et al. In these papers they have regarded the loaded coil as a lumped impedance, and have analyzed the antenna by treating the coil as an equivalent slice generator.

Generally treating the coil as a lumped impedance, the calculated current distributions of the coil-loaded antenna are often different from the measured results.

In this paper, by approximating the coil as a sheath helix, we derive the integral equation for the coil-loaded antenna. The current distribution is calculated numerically by the moment method and the results show the good agreement with the measured results, compared with the conventional method which treats the coil as a lumped impedance.

2. Integral equation

The coil-loaded dipole antenna is shown in Fig.1(a), (b). Fig.1(a)
shows an actual model and Fig.1(b) shows the analysis model of Fig.1(a).

In this model, taking an observation point on the axis of antenna, we obtain the following integral equation,

$$\frac{1}{j\omega\varepsilon} \left\{ \frac{\partial}{\partial z} \left( \frac{\partial E(z', z')}{\partial z} \right) - R(z') \frac{\partial}{\partial z} \phi(z, z') \right\} dz' $$

$$= -E_{x}^{0}(z) - E_{x}^{m}(z) \quad (1)$$

where $\psi = \exp(-jkr)/R$, $R$ denotes the distance between the movable point on the antenna surface and the observation point on the axis.

In the above equation, $E_{x}^{0}(z)$ and $E_{x}^{m}(z)$ denote the contribution from the coil parts $L_{c}$ and the feed region respectively. $E_{x}^{c}$ is described by

$$E_{x}^{c} = \frac{1}{j\omega\varepsilon} \left\{ \frac{\partial}{\partial z} \left( \frac{\partial E(z', z')}{\partial z} \right) + R(z') \frac{\partial}{\partial z} \phi(z, z') \right\} dz'$$

$$+ 2\pi a_{c} \int_{L_{c}} E_{x}(z') \frac{\partial \phi(z, z', r')}{\partial r'} \bigg|_{r' = a_{c}} dz'$$

Fig.1 The coil-loaded dipole antenna ((a) actual model, (b) analysis model).
\[
\left[ \frac{\mathbf{v} \cdot \mathbf{V}}{\varepsilon \omega} \right] \mathbf{E} \cdot \mathbf{n}_z + \mathbf{m}_z \cdot \left[ (\mathbf{m} \times \mathbf{E}) \times \mathbf{V} \psi \right] \right] dS'
\]

where \( \text{Sc} \) is the coil end surface and \( a_c \) is the radius of coil, \( m \) and \( m_z \) denote outward and \( z \)-directional normal vectors respectively.

In the analysis of loaded antenna it is very important how we express the coil section or \( \mathbf{E} \). In the next section we will treat the coil as a sheath helix approximately and evaluate \( \mathbf{E} \).

3. Analysis of sheath helix

The sheath helix, which has infinite conductivity for hericalward and zero for outward, has been analyzed for the approximate model of general helical structure.

Fig. 2 shows the sheath helix of an infinite length. The electric field \( E_z \) satisfies the following wave equation

\[
\nabla^2 E_z + k^2 E_z = 0
\]

If the component \( E_0 \) could be ignored, then the solution of (3) is given by

\[
E_z(r,z) = \begin{cases} 
A_0 I_0(\beta_0 r) e^{i\alpha_0 Z} & (r \leq a_c) \\
B_0 K_0(\beta_0 r) e^{-i\alpha_0 Z} & (r > a_c)
\end{cases}
\]

where \( I_0 \) and \( K_0 \) are the modified Bessel function of the first and second kind of zero order respectively, and \( \beta_0 \) is the phase velocity of \( z \)-directional and \( \alpha_0 = \gamma_0^2 + k_0^2 \). \( A_0 \) and \( B_0 \) are arbitrary constants.

Since the magnetic field also satisfies the wave equation, \( H_z \) is given by the similar formula to (4). The solutions of the other components are derived from \( E_z \) and \( H_z \) by substituting Maxwell's equation, and applying the boundary condition on the surface of sheath helix to these solutions, then the following equation is obtained:

\[
(k a_c \cot \Phi)^2 = (\gamma_0 a_c)^2 \frac{I_0(\gamma_0 a_c) K_0(\beta_0 a_c)}{I_1(\gamma_0 a_c) K_1(\beta_0 a_c)}
\]

(5)

In the above equation \( I_1 \) and \( K_1 \) are the preceding modified Bessel function of first order, \( \Phi \) is the pitch angle of the helix and \( a_c \) is the radius of helix.

From (5) and the relation \( \beta_0^2 = \gamma_0^2 + k_0^2 \), we can obtain the phase velocity \( \beta_0 \).

Considering both traveling and reflecting waves, \( E_z \) and \( H_0 \) are expressed as follows

\[
E_z(z) = I_0(\gamma_0 a_c) \left( A_0^+ e^{i\beta_0 Z} + A_0^- e^{-i\beta_0 Z} \right)
\]

(6)

\[
H_0(z) = -\frac{i\omega \varepsilon}{\mu_0} \frac{I_0(\gamma_0 a_c)}{K_0(\beta_0 a_c)} K_1(\gamma_0 a_c) \left( A_0^+ e^{i\beta_0 Z} + A_0^- e^{-i\beta_0 Z} \right)
\]

(7)
Fig. 4 Current distributions of loaded antenna located the coil intermittently (z=±2/3h).

Fig. 5 Current distributions of loaded antenna located the coil near the antenna end (z=±9/10h).

References

where $A_0^+$ and $A_0^-$ are the arbitrary constants of reflecting and traveling wave.

4. Current and electric field on the coil

The coil-end currents have the following relations

$$I^c(z_1) = 2\pi a_c H_0(z_1) = I_1, \quad I^c(z_2) = 2\pi a_c H_0(z_2) = I_2$$  \(8\)

where, as shown in Fig. 3, $I_1$ and $I_2$ are the current values at the coil end.

Then using $I_1$ and $I_2$, we can describe $A_0^+$ and $A_0^-$ as

$$
\begin{pmatrix}
A_0^+ \\
A_0^-
\end{pmatrix} = -\frac{\gamma_0}{4\pi a_c \omega E \sin(\beta_0 L_c)} \cdot \begin{pmatrix}
K_0(\gamma_0 a_c) \\
\gamma_0 a_c K_1(\gamma_0 a_c)
\end{pmatrix}
\begin{pmatrix}
I_1 e^{j\beta_0 Z_2} + I_2 e^{j\beta_0 Z_1} \\
- I_1 e^{j\beta_0 Z_2} + I_2 e^{j\beta_0 Z_1}
\end{pmatrix}
$$  \(9\)

Thus we obtain

$$I^c(z) = \frac{1}{\sin(\beta_0 L_c)} \left\{- I_1 \sin(\beta_0(z-Z_2)) + I_2 \sin(\beta_0(z-Z_1)) \right\}$$  \(10\)

$$E_x(z) = Z_{LE} I^c(z)$$  \(11\)

$$Z_{LE} = \frac{\gamma_0}{2\pi a_c \omega E} \cdot \begin{pmatrix}
K_0(\gamma_0 a_c) \\
\gamma_0 a_c K_1(\gamma_0 a_c)
\end{pmatrix}$$  \(12\)

where $L_c = (z_2-z_1)$ is the height of coil.

By (10)-(12) and (1), we can solve numerically the coil-loaded antenna by using the moment method.

5. Results and discussions

The coil-loaded antenna used in the experiment is a half wave dipole of the radius $0.001$ wave length. The loaded coil is made of $1.2$mm diameter copper wire. The coil radius and its pitch are $15$mm, $2$mm respectively. Here used the frequency of $300$ MHz.

The numerical calculation is done by applying the moment method to (1). The current on the surface of antenna is expanded by the piecewise sinusoidal function and also on the coil surface.

Fig. (4) and (5) show the experimental and calculated current distributions of the coil-loaded dipole. In the case located a coil at $z=\pm2/3h$, the calculated results agree with the measured results.

In the case located a coil near the antenna end, as shown Fig. 5, the calculated results regarded the coil as a lumped impedance do not agree with the measured results but the results by our method show a good agreement.

6. Conclusion

For the analysis of coil-loaded antenna, a method by approximating the loaded coil as a sheath helix has been studied and its availability has been confirmed numerically and experimentally.

For the given values of turns and pitch angle of the coil, we can calculate the characteristics of the coil-loaded antenna easily without measuring the impedance of the coil.