Miklós KUCZMANN

"Széchenyi István" University

Feeding models of wire antennas

***Abstract**. Antenna parameters (e.g. input impedance, radiation pattern) can be measured in Full Anechoic Chambers (FAC). The simulated input impedance is depending on the applied feed model. The most frequently used models are the current probe model, the voltage gap generator, the magnetic frill generator and the waveguide port which are presented in this paper focusing on a simple example, a monopole antenna situated above a ground plane. The Finite Element Method (FEM) has been used in the numerical field analysis.*

***Streszczenie.** Parametry anteny (np. impedancja wejściowa, własności promieniowania)mogą być zmierzone w komorze bezodbiciowej. Zasymulowana impedancja wejściowa zależy od modelu zasilania anteny. Najczęściej spotykane modele: model sondy prądowej, generator napięciowy ze szczeliną, frill generator, oraz falowód, pokazane są w artykule z naciskiem na prosty przykład anteny jednobiegunowej umieszczonej nad płaszczyzną gruntu. Metod elementów skończonych została użyta w analizie numerycznej. (**Modele zasilania anten obwodowych**)*

Keywords: antenna feeding, antenna parameters, finite element method.
Słowa kluczowe: zasilanie anteny, parametry anteny, metoda elementów skończonych

Introduction

The most important measured parameters of an antenna are the input impedance and the radiation pattern. Other parameters, such as the reflection coefficient or the voltage standing-wave ratio can be calculated from the input impedance, the directivity as well as the gain can be obtained from the radiation pattern. The simulated input impedance is depending on the applied feed model that is why it is very important to know the advantages and the disadvantages of the feeding models. The most frequently used models are the current probe model, the voltage gap generator, the magnetic frill generator and the waveguide port. This paper presents the above mentioned approaches through a monopole antenna situated above a ground plane. The Finite Element Method (FEM) has been used in the numerical field analysis, which is a widely used technique to solve partial differential equations obtained from Maxwell's equations. Here, Helmholtz equation for the magnetic field intensity is studied in two dimensions supposing axial symmetry and in three dimensions modeling the complete geometry of the antenna. First, the problem and the corresponding equations are shown, and then the four feeding models are described. After the presentation of numerical results, a short discussion closes the paper.

Finite Element Method in Antenna Simulation

The Finite Element Method is a widely used numerical technique in computer aided design of electrical engineering problems. Only a brief introduction can be written here, the focus is only on the antennas and the corresponding equations. A detailed description can be found in [3-5].

The basis of the technique is the discretization of the problem region by simple finite elements. These finite elements are the triangle and the quadrangle in two dimensional problems, or the tetrahedral, hexahedral and prism elements in three dimensional problems. The system of equations to be solved for the potentials or for the field quantities can be assembled after obtaining the weak formulation of the partial differential equations and the boundary conditions of the problem. The latter equations can be derived from Maxwell's equations [3-5,7].

(1) $\nabla \times \boldsymbol{H} = \mathrm{j}\omega\varepsilon\boldsymbol{E}$,

(2) $\nabla \times \boldsymbol{E} = -\mathrm{j}\omega\mu\boldsymbol{H}$,

(3) $\nabla \cdot \boldsymbol{H} = 0$,

(4) $\nabla \cdot \boldsymbol{E} = 0$,

where $\boldsymbol{H}$, $\boldsymbol{E}$, ω, ε, and μ are the magnetic field intensity and the electric field intensity, the angular frequency of excitation, the permittivity and the permeability, respectively. The phasor representation has been used, because of the time-harmonic excitation (the generator is supposed to be sinusoidal), i.e. $\mathrm{j}^2 = -1$ is the imaginary unit.

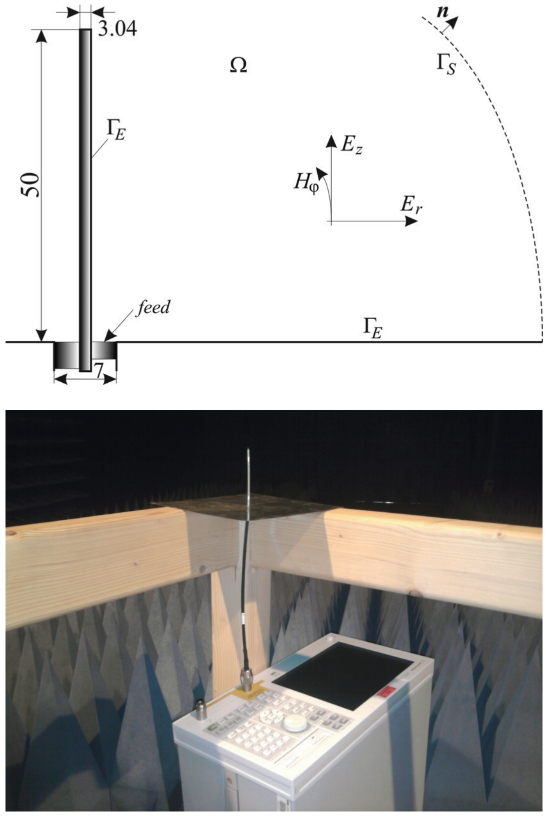

Fig.1. The geometry of the monopole antenna and the measurement system in FAC

It is well known that the electromagnetic field of the monopole antenna is transverse magnetic (TM) [3,4,7], or in other words, the magnetic field has only one component in the φ-direction, and the electric field has two orthogonal components, as it is denoted in Fig. 1.

The electric field intensity must be normal to the surface of the ground plane and the surface of the antenna, i.e. the boundary condition

(5) $\boldsymbol{E}\times\boldsymbol{n}=\boldsymbol{0}$

can be supposed on Γ_E, and ***n*** is the outer normal unit vector.

On Γ_S, absorbing boundary condition must be prescribed to absorb the electromagnetic energy [3,4],

(6) $\lim_{r\to\infty} r\left[\nabla\times\boldsymbol{H}+\mathrm{j}k_0\,\boldsymbol{n}\times\boldsymbol{H}\right]=\boldsymbol{0}$, on Γ_S,

which can be approximated by the first order absorbing boundary condition

(7) $\boldsymbol{n}\times\left[\nabla\times\boldsymbol{H}+\mathrm{j}k_0\,\boldsymbol{n}\times\boldsymbol{H}\right]=\boldsymbol{0}$, on Γ_S,

where $k_0=\omega\sqrt{\mu\varepsilon}$ is the wavenumber in free space ($\mu=\mu_0$, $\varepsilon=\varepsilon_0$). This models the unbounded space. The calculation domain must be truncated somehow, because the discretization can not be performed at infinity, and the condition (7) on Γ_S can be used to decrease the domain volume. The efficiency of absorbing the electromagnetic energy along the boundary Γ_S can be increased by applying a perfectly matched layer (PML) which outer boundary has been assigned as the absorbing boundary [3].

Finally, $\boldsymbol{H}\times\boldsymbol{n}=\boldsymbol{0}$ must be satisfied along symmetry planes (along the line $r=0$ in axial symmetry situations).

It is evident that the application of the magnetic field intensity as the primary variable results in the most economic formulation. The partial differential equation to be solved for the magnetic field intensity here is the following [3,7]:

(8) $\nabla\times\nabla\times\boldsymbol{H}-k_0^2\boldsymbol{H}=\boldsymbol{0}$,

and $\boldsymbol{E}=(\nabla\times\boldsymbol{H})/\mathrm{j}\omega\varepsilon$ is the electric field intensity from (1) and (2). After some mathematical manipulations and using (3), the following partial differential equation can be obtained for H_φ:

(9) $\Delta H_\varphi+k_0^2 H_\varphi=0$,

which is a scalar Helmholtz equation of the magnetic field intensity.

Feeding models in FEM

The feeding models of antennas are applied to take the input of the antenna into account. The most widely used feeding models are shown in Fig. 2 [1-3,6].

The most widely used current probe model is a short current with a delta function, e.g.

(10) $\boldsymbol{J}(x,y,z)=\boldsymbol{e}_z\,I_0\,\delta(x-x_f,y-y_f)$, $0\le z\le d$.

It models a wire with zero diameter, x_f and y_f are the coordinates of the current I_0 ($x_f=0$, and $y_f=0$ in Fig. 2. a), and ***J*** has only one component in the *z* direction. This infinitesimal dipole can be generalized in any direction of the space. The electromagnetic field is singular in the vicinity of the probe [3]. This is the reason why it is more convenient to prescribe the magnetic field intensity on the surface of the antenna wire as it is represented in Fig. 2. a. The φ-component of the magnetic field intensity can be calculated by

(11) $H_\varphi=\dfrac{I_0}{2a\pi}$, $0\le z\le d$,

and $a=1.52\,\mathrm{mm}$ is the radius of the antenna. The length of the probe in the *z* direction should be as small as possible, but it can be concluded that $l \ll \lambda$ must be specified, and λ is the wavelength of the electromagnetic wave in vacuum, $\lambda=c/f$ (*c* is the speed of light and *f* is the frequency of excitation). Here $d=1.6\,\mathrm{mm}$ has been used.

Once the electric field ***E*** is determined by the applied numerical method, the voltage across the probe can be computed as

(12) $U=-\int_0^d E_z(\mathrm{r}=\mathrm{a})\,\mathrm{d}z$,

and the input impedance of the antenna is

(13) $Z=\dfrac{U}{I_0}$.

The current distribution along the antenna can be calculated by the following form of Ampere's law:

(14) $I(z)=2a\pi\,H_\varphi(z)$.

The voltage gap generator model is basically used in the Method of Moments (MoM) plane as it is presented in Fig. 2. b. The *z* component of the electric field can be obtained by

(15) $E_z=-\dfrac{U_0}{d}$

in the gap ($0\le z\le d$), and *d* the length of the gap. The electric field intensity is prescribed along the line $r=a$, and $0\le z\le d$ (see in Fig. 2. b).

The current in the feeding point then can be calculated by (14) substituting $z=0$, i.e.

(16) $I=2a\pi\,H_\varphi(z=0)$,

then the input impedance can be obtained by

(17) $Z=\dfrac{U_0}{I}$.

The current distribution along the antenna can be simulated by (14).

The magnetic frill generator is a model of the antenna input fed by a coaxial line [1]. The following electric field intensity can be supposed in the radial direction by assuming purely TEM mode inside the coaxial transmission line (see in Fig. 2. c.):

(18) $E_r(r)=\dfrac{U_0}{2r\ln(b/a)}$, $a\le r\le b$,

where *a* and *b* are the inner and outer radius of the coaxial line ($a=1.52\,\mathrm{mm}$ and $b=3.5\mathrm{mm}$) and U_0 is the potential difference between the inner wire and the outer shielding. The current distribution along the antenna can also be simulated by (14), and the input impedance can be calculated in the same way as presented in the case of voltage gap generator.

The waveguide port model is more accurate and more efficient approach in general case. This is based on the weighted sum of TEM, TE and TM waveguide modes, and the weighting coefficients are collected in tables [3]. This model has been implemented in Comsol Multiphysics [8]. The scattering parameter (reflection coefficient) S_{11} can be extracted from the simulated electric field, finally, the input impedance can be obtained as [3,8]

$$(19)\quad Z = Z_0 \frac{1+S_{11}}{1-S_{11}},$$

where $Z_0 = 50\Omega$ is the characteristic impedance of the waveguide.

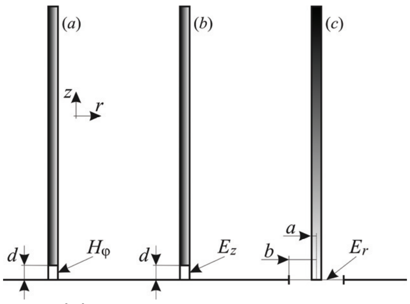

Fig.2. Feeding models

Simulation results

The problem has been solved by the functions of the Radio Frequency module of Comsol Multiphysics [8]. This software is a very efficient FEM design environment. The above mentioned feeding models can be implemented and tried out in an easy way. The models can be downloaded from the Author's homepage [9].

First, the φ-component of the magnetic field intensity has been simulated by the TM Electromagnetic Waves application mode, and two dimensional axial symmetry geometry has been analyzed for simplicity, because the aim is the study of the different models. Second order Lagrange shape functions have been used to approximate the unknown field quantity. Second, the whole 3D problem has been analyzed aiming to compare the two dimensional and the three dimensional results. In 3D vector shape functions have been used [3-5].

After some trials, 55296 triangles have been used to mesh the two dimensional geometry, and it results in 111329 unknowns. In 3D, 36682 tetrahedra have been generated, which results in 247814 unknowns. This is a very dense mesh and it can be seen in Fig. 3.

The convergence of the simulated input impedance can be seen in Fig. 4, where the measured impedance is also shown. Measured data are from [2]. The variation of input impedance is practically the same when applying finer and finer mesh. There is a permanent difference between measured and simulated data.

The geometry of the antenna has been subtracted from the calculation domain, because it is supposed to be made of ideal conducting material, i.e. discretization is not necessary inside the wire. The same mesh has been used in all the frequency during the frequency sweep in the range of 1GHz and 4.5GHz. A PML layer [3,8] has been inserted to improve the absorption of electromagnetic field, and the radius of the computational domain is 1m in the two dimensional case and it is 0.25 m in the three dimensional case.

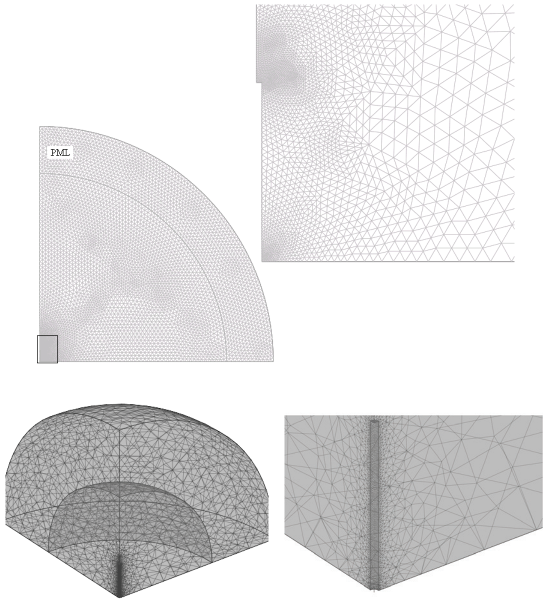

Fig. 3. FEM mesh in 2D and in 3D, the vicinity of antenna is magnified

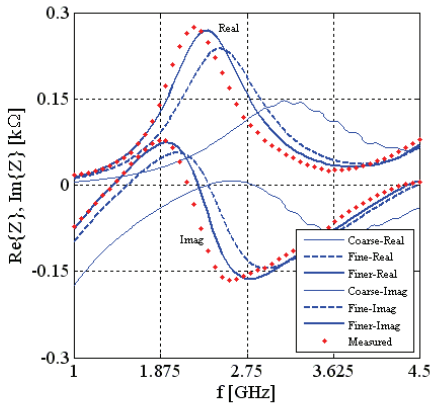

Fig. 4. Convergence of the solution vs. number of triangles

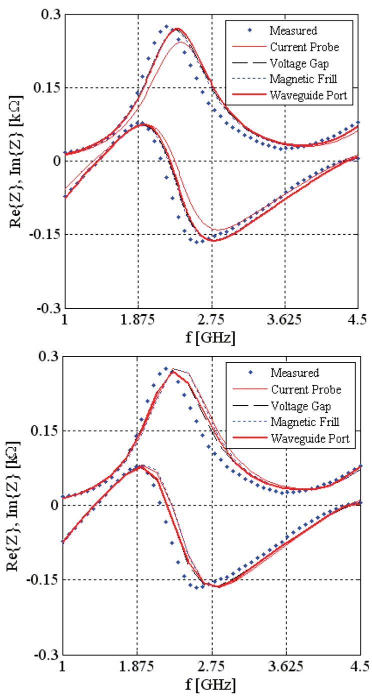

Fig. 5. Comparison of the input impedance of the monopole antenna (up—2D simulations, down—3D simulations)

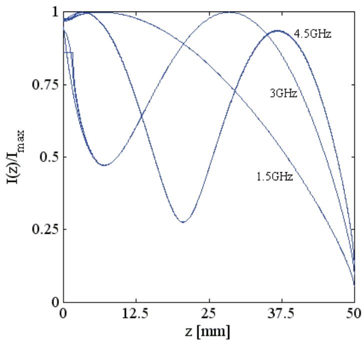

Fig. 6. Normalized current distribution along the antenna at three different frequencies

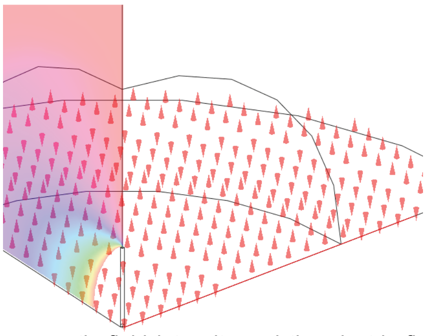
Fig. 7. The magnetic field intensity and the electric field intensity around the antenna

Fig. 5 shows a comparison between measured input impedance and simulated ones. The application of current probe model results in the weakest approximation, the approximated value obtained from the other models are practically the same. The results from the 2D and 3D simulations are the same, i.e. the mentioned feeding models can be used in any three dimensional situations.

The current distribution along the antenna is a very important input data to calculate other quantities. A comparison between the obtained currents simulated by the above mentioned feeding models can be seen in Fig. 6 at the frequencies $f = 1.5\text{GHz}$, $f = 3\text{GHz}$, and $f = 4.5\text{GHz}$. The results are practically the same, but a small difference can be seen in the vicinity of $z = 0$ (the feeding point), and it is the effect of the different feeding models. Fig. 7 shows a very spectacular three dimensional result. The variation of the electric field intensity is presented as normalized vectors on the plane $z = 0$. The magnetic field intensity is also shown in the figure as a slice on the plane $x = 0$.

Conclusion

Feeding models of antennas have been presented in the frame of FEM. The input impedance, the current distribution of a monopole antenna on a ground plane and the variation of electromagnetic field quantities around the antenna have been simulated and compared with measured data.

The next step of the research work is to apply the feeding models in the case of more complex antennas in three dimensional situations, and to compare the results with other numerical techniques, e.g. with MoM.

Acknowledgements: This paper was supported by Széchenyi István University (15-3210-02), by the Hungarian Scientific Research Fund (OTKA PD 73242).

REFERENCES

[1] Gibson, W.C., *The Method of Moments in Electromagnetics*, Chapman & Hall/RCR, 2008.
[2] Hertel, T., Smith, G., On the convergence of common FDTD feed models for antenna, *IEEE Trans. Antennas Propag.*, 51 (2003), 1771–1779.
[3] Jin, J-M., Riley, D.J., *Finite Element Analysis of Antennas and Arrays*, Wiley, IEEE Press, 2009.
[4] Jin, J-M., *The Finite Element Method in Electromagnetics*, Wiley, IEEE Press, 2002.
[5] Kuczmann, M., Iványi, A., *The Finite Element Method in Magnetics*, Academic Press, Budapest, 2008.
[6] Lou, Z., Jin, J-M., Modeling and simulation of broad-band antennas using the time-domain finite element method, *IEEE Trans. Antennas Propag.*, 53 (2005), 4099–4110.
[7] Simonyi, K., Zombory, L.: *Theoretical electromagnetics*, Műszaki Könyvkiadó, Budapest, 2000.
[8] http://www.comsol.com
[9] http://maxwell.sze.hu/~kuczmann/Korszeru_antenna/Antenna_lap.htm

***Authors**: Dr. Miklós Kuczmann, PhD, Széchenyi István University, Department of Telecommunications, Laboratory of Electromagnetic Fields, Egyetem tér 1, H-9026 Győr, Hungary, E-mail: kuczmann@sze.hu.*