

Open source ELMER software based FEM modeling of waveguides and resonant cavities for microwave heating and drying devices

JAKUB SZALATKIEWICZ¹, ROMAN SZEWCZYK², MATEUSZ KALINOWSKI¹,
JUHANI KATAJA³, PETER RÅBACK³, JUHA RUOKOLAINEN³, MACIEJ KACHNIARZ²

¹*Industrial Research Institute for Automation and Measurements PIAP
al. Jerozolimskie 202, 02-486 Warsaw, Poland*

²*Institute of Metrology and Biomedical Engineering, Warsaw University of Technology
sw. Andrzeja Boboli 8, 02-525 Warsaw, Poland
e-mail: r.szewczyk@mchtr.pw.edu.pl*

³*CSC – IT Centre for Science, P.O Box 405, FI-02101 Espoo, Finland*

(Received: 30.09.2016, revised: 18.02.2017)

Abstract: Microwave devices are widely used in the industry and in the specialized laboratory analyses. Development of such devices requires the possibility of modeling of microwave energy distribution in the specific resonant chambers. Until now, such modeling was possible only with the use of commercial software or was limited to specific cases. The paper presents an open-source module for ELMER software for solving time-harmonic Maxwell's equations, allowing modeling of microwave waveguide lines. Three test cases of different resonant chambers are investigated at 2.45 GHz frequency. Modeling results obtained from the open-source ELMER Vectorial Helmholtz module show that the application of this software can be effective in R&D works, enabling high-tech small and medium enterprises involvement in advanced microwave technology.

Key words: microwave, waveguide, resonant cavity, FEM modeling, ELMER software, open source

1. Introduction

Modeling of key elements of developed devices is an important part of the development process, reducing its cost and increasing its efficiency. The most flexible method of this modeling, commonly implemented in commercial development tool chains is the finite element method (FEM) [1]. However, development of special devices, such as microwave chambers for drying e. g. in the food industry [2], require specialized modeling software, which is expensive. As a result, development of special microwave devices is monopolized by large-scale

companies, which are able to cover significant investment costs at the beginning of the development process.

Recently, the open source modeling software is becoming a more and more important alternative for the commercial programs, which creates the possibility of development for small enterprises. One of such solutions is ELMER, enabling FEM modeling of mechanical, thermal, electrical and magnetic systems. However, until now, it was not possible to model microwave systems with this software, which makes microwaves one of the last area, where FEM modeling during the development of devices was limited by necessity of large investment in commercial modeling software.

This paper presents the solution overcoming this problem. An open source ELMER finite element method oriented software [3] was equipped in a module enabling the calculation of microwave distribution in the resonant chamber. Open source Delaunay tetrahedral meshing modules [4], visualization software and solvers using conjugate gradient-oriented algorithms previously available in ELMER were applied to solve the proposed set of differential equations.

2. Method of modeling

Real technical cases, described by the full set of differential Maxwell equations, are very difficult to be modelled, even using advanced methods and high power computers [5]. For this reason, Maxwell equations are reduced to describe the specific cases, such as magnetostatic, magnetodynamic, optics or microwaves.

In the developed module, the time-harmonic Maxwell equation system for magnetic field $B = B_0 e^{-i\omega t}$ is given as [6]:

$$\mu^{-1} \nabla \times \mathbf{E} = i\omega \mathbf{H} \quad , \quad (1)$$

$$\nabla \times \mathbf{H} = -i\omega \epsilon \mathbf{E} + \mathbf{J} \quad , \quad (2)$$

$$\omega = 2\pi f \quad , \quad (3)$$

$$\mu = \mu_0 \mu_r \quad , \quad (4)$$

$$\epsilon = \epsilon_0 \epsilon_r \quad , \quad (5)$$

where: f is the frequency of the electromagnetic field, μ_0 is the magnetic permeability of free space, μ_r is the relative magnetic permeability, ϵ_0 is the electric permittivity of free space and ϵ_r is the relative electric permittivity of material. \mathbf{E} , \mathbf{H} and \mathbf{J} are: an electric field vector, magnetic field vector and current density vector respectively.

In the developed Vectorial Helmholtz module for electromagnetic (microwave) calculations in ELMER, two kinds of boundary conditions are implemented. The Leontovich impedance boundary, where conductivity σ_c and permeability μ_c are bulk conductivity and permeability of the wall, is described by the Robin boundary condition [7, 8]:

$$\alpha = -i\omega\mu Z_p^{-1} \text{ and } \mathbf{g} = 0, \quad (6)$$

where: \mathbf{g} is the given vector function defined on $\partial\Omega$, which is the boundary of the computational domain Ω on which the equation is to be solved. It can be described with the equation:

$$\mathbf{g} = \mathbf{n} \times \nabla \times \mathbf{E} - \alpha \mathbf{n} \times (\mathbf{n} \times \mathbf{E}). \quad (7)$$

Z_p is the surface impedance given as:

$$Z_p = (1-i) \sqrt{\frac{\mu_c \omega}{2\sigma_c}}. \quad (8)$$

The second kind of boundary is the first order absorbing boundary. The computational domain is now B_R and ∂B_R is the boundary of the domain. It can be given as [7, 8]:

$$\mathbf{n} \times \nabla \times \mathbf{E} = i\omega \sqrt{\varepsilon_0 \mu_0} \mathbf{n} \times (\mathbf{n} \times \mathbf{E}) \text{ on } \partial B_R. \quad (9)$$

This leads to the Robin boundary condition [7, 8]:

$$\alpha = i\omega \sqrt{\varepsilon_0 \mu_0} \text{ and } \mathbf{g} = 0. \quad (10)$$

Moreover, port feed is given by the following equations [7, 8]:

$$\alpha = -i\beta \text{ and } \mathbf{g} = 2i\beta(\mathbf{n} \times \mathbf{E}) \times \mathbf{n}, \quad (11)$$

where: \mathbf{E}_p is a wave propagating through the port feed, β is a propagation constant.

Finite element modeling requires three main steps: meshing of the objects, solving the finite element differential equations and visualization of the results.

Open-source meshing software is dominated by NETGEN [9] developed mostly by Prof. Joachim Schöberl and his team of Johannes Kepler University Linz and GMSH [10] developed by Prof. Christophe Geuzaine of University of Liège and Prof. Jean-François Remacle of Université Catholique de Louvain. Modules of this software are implemented in other FEM toolchains, such as SALOME.

ELMER FEM [3] is the most advanced finite element differential equation solver available as an open source. It implements most of the models of physical systems (covering mechanical, thermal, electrical and magnetic) as well as the set of solvers based on the conjugate gradient method, optimized for large-scale calculations. It should be stressed that ELMER natively works in the Linux systems, where matrix-oriented, multicore calculations can be performed very efficiently using openBLAS [11] and ATLAS [12] libraries. WINDOWS-based compilations are available, however, they are significantly slower.

The last step is visualization of the results of calculations. Natively for ELMER FEM, visualization may be done with a built-in VTK module [13]. It is also possible to visualize the results of modeling with more advanced PARAVIEW [14] or SALOME [15] software.

It should be stressed, that the background of ELMER FEM development is not only open-source but also an open-standard approach. This means that both input and output file stan-

dards are available, and both meshing and visualization of the results may be performed by a wide range of software (both open-source and commercial).

3. Tetrahedral meshing

Fig. 1 presents the examples of the results of tetrahedral meshing of two microwave sets. The first one is a rectangular cavity with a microwave port. The second is a standardized WR340 waveguide for 2.45 GHz with a cylindrical cavity attached to one of its end. Meshing was performed by NETGEN software.

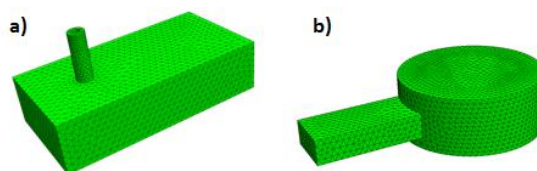


Fig. 1. Tetrahedral meshing of two microwave sets: a) rectangular cavity with microwave port; b) standardized WR340 waveguide for 2.45 GHz with cylindrical cavity attached

4. Results of modeling

Fig. 2 presents the results of simulations of electric field amplitude for two rectangular cavities with the microwave feeding port.

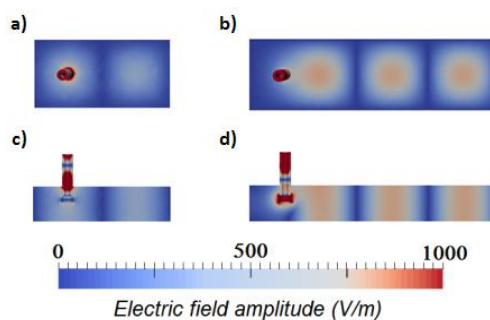


Fig. 2. The results of simulations of electric field amplitude for two rectangular cavities with the microwave feeding port: a) cavity length equal to 130.5 mm, top view; b) the length equal to 260.1 mm, top view; c) cavity length equal to 130.5 mm, side view; d) cavity length equal to 260.1 mm, side view

The length of the first cavity was 130.5 mm, whereas the length of the second cavity was 260.1 mm. The microwave port was fed with a frequency of 2.45 GHz. In both cases the standing wave can be observed, however, the amplitude of the waves in the second case is higher.

Fig. 3 presents the directions of the vector of a magnetic and electric field in the first cavity with a length equal to 130.5 mm. It can be seen that the magnetic field is rotating, whereas the electric field is in the direction of the symmetry axis feeding port.

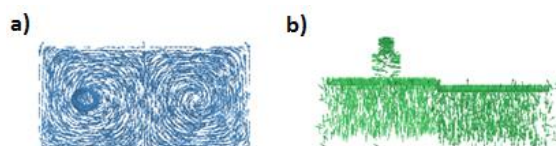


Fig. 3. Spatial distribution of vectors in a rectangular cavity with a length equal to 130.5 mm:
a) magnetic field; b) electric field

Fig. 4 presents the results of optimization of the cylindrical cavity of the microwave dryer. A standardized WR340 waveguide for 2.45 GHz was attached to one of cylindrical cavities with a different diameter. It can be clearly seen that the resonance in the cavity occurs for its diameter equal to 250 mm.

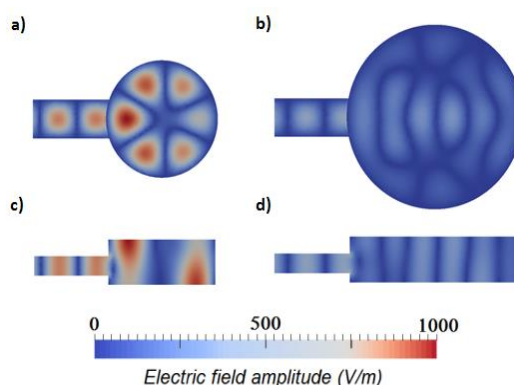


Fig. 4. Distribution of the amplitude of an electric field in cylindrical cavities attached to WR340 waveguide (frequency $f = 2.45$ GHz). Cavities with diameter: a) 250 mm, top view; b) 400 mm, top view; c) 250 mm, side view; d) 400 mm, side view

5. Conclusion

The presented results indicate that it is possible to perform 3D simulations of microwave devices using open-source software for the finite element method. Moreover, such simulation may be carried out using NETGEN software for meshing, ELMER FEM for model definition and solving the set of differential equations, as well as a VTK toolbox for visualization of the results.

The presented results confirm that optimization of the dimensions of microwave cavities may be performed using the presented software. Moreover, the occurrence of the standing

wave and the resonance may be predicted and the value of amplitude of electrical field may be assessed. Such simulations, based on the open-source software are especially important for small, high-tech companies involved in microwave technology.

Acknowledgements

This work was carried out within a research project no. PBS2/B3/18/2013 financed by The National Center for Research and Development

References

- [1] Zienkiewicz O., Taylor R.L., Zhu J.Z., *The Finite Element method: Its Basis and Fundamentals*, Butterworth-Heinemann (2005).
- [2] Krokida M.K., Maroulls Z.B., *Effect of microwave drying on some quality properties of dehydrated products*, *Drying Technology*, vol. 17, no. 3, pp. 449-466 (1999).
- [3] Råback P., Malinen M., *Overview of Elmer*, CSC- IT Centre for Science (2016).
- [4] Cignoni P., Montani C., Scopigno R., *DeWall: A fast divide & conquer Delaunay triangulation algorithm in E^d* , *Computer-Aided Design*, vol. 30, no. 5, pp. 333-341 (1998).
- [5] Šolín P., *Partial differential equations and the finite element method*, John Wiley & Sons (2006).
- [6] Råback P., Malinen M., Ruokolainen J., Pursula A., Zwinger T. (Eds.), *Elmer Models Manual*, CSC- IT Centre for Science (2016).
- [7] Jackson J.D., *Classical Electrodynamics*, John Wiley & Sons (1999).
- [8] Peterson A.F., *Absorbing boundary conditions for the vector wave equation*, *Microwave and Optical Technology Letters*, vol. 1, no. 2, pp. 62-64 (1988).
- [9] Schöberl J., *NETGEN An advancing front 2D/3D-mesh generator based on abstract rules*, *Computing and Visualization in Science*, vol. 1, no. 1, pp. 41-52 (1997).
- [10] Geuzaine C., Remacle J.F., *Gmsh: A 3-D finite element mesh generator with built-in pre- and post-processing facilities*, *International Journal for numerical Methods in Engineering*, vol. 79, no. 11, pp. 1309-1331 (2009).
- [11] Wang Q., Zhang X., Zhang Y., Qing Y., *AUGEM: automatically generate high performance dense linear algebra kernels on x86 CPUs*, *International Conference on High Performance Computing, Networking, Storage and Analysis*, Denver, USA, no. 25 (2013).
- [12] Whaley C.R., Petitot P.A., Dongarra J., *Automated Empirical Optimization of Software and the ATLAS Project*, *Parallel Computing*, vol. 27 (2000).
- [13] <http://www.vtk.org>, accessed October 2016.
- [14] <http://www.paraview.org>, accessed October 2016.
- [15] <http://www.salome-platform.org>, accessed October 2016.