Neural Network-Based Software Package for Loaded Microwave Cavity Characterization

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Abstract – **Software package MW-Cavity for a resonant frequency determination of loaded microwave cavity is presented in this paper. The package is based on the multilayer perceptrons (MLP) neural network modeling of different TM/TE$_{mnp}$ modes excited in a loaded cylindrical metallic cavity. For chosen dielectric slab parameters combination, the current version of presented software provides a fast simulation and accurate resonant frequency determination of eight TE$_{mnp}$ and eight TM$_{mnp}$ modes with the lowest resonant frequencies in empty cavity. Owing to mentioned capabilities, MW-Cavity can be used for an efficient analysis of the experimental loaded microwave cavity as well as for an identification process of the modes excited in such cavity.**

Keywords – **microwave cavity, dielectric slab, resonant frequency, neural network, software package**

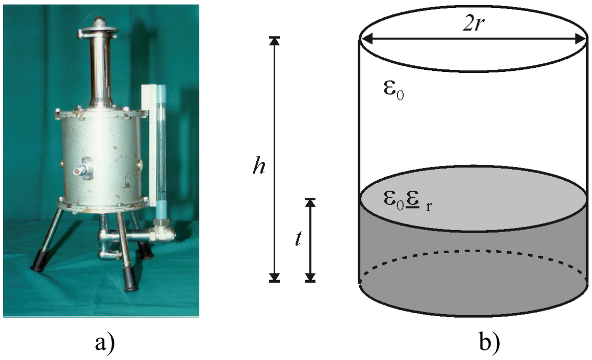
I. INTRODUCTION

In the last few decades, intensive progress of microwave technique has lead to a wide use of microwave applicators in science, industry and medicine. Cylindrical metallic cavities represent mostly used applicator configurations [1-4]. Such cavities have a very important role in the processes of dielectric material heating and drying by microwave energy. In order to design the resonant applicator with a high efficiency of dielectric material heating, it is important to determine and then control the dynamic process of heating in resonant ovens at the electromagnetic (EM) level. Therefore, the knowledge of EM wave resonant modes that can be excited in the cavity and the determination of their resonant frequencies behavior under different cavity dimensions and different EM and physical properties of cavity load, form an integral part of the studies in microwave heating and it can considerably help in designing microwave applicators.

Transverse resonance method (TRM) is a conventional approach for carrying a theoretical analysis of cylindrical metallic cavities [1]. This method is not too complicated for a software implementation, but it is applicable mainly to the case of homogeneous cavity loads with a planparallel layers form. For the purpose of modeling of cavities loaded by dielectric materials of complex geometry and inhomogeneous EM properties, some of advanced numerical simulation techniques, such as transmission line matrix (TLM) method [2], finite difference time domain (FD-TD) method or finite element method (FEM), have to be used. However, the common disadvantage of all advanced numerical approaches is that they are hardware and time consuming, which can sometimes limit their application for the analysis of loaded cavities. Approximate model of loaded microwave cavity presented in [3], unlike detailed EM model, does not require powerful hardware platform and it does not use complex numerical calculations for resonant frequency determination, but on the other side it has a limited accuracy.

Artificial neural networks exhibit the well known properties such as fast signal propagation through their structure, ability to easily adapt to the problem nature and capacity to generalize the problem even in a case when problem physics is not fully understood and it can not be fully described with explicit functional dependences. Therefore, models based on neural networks represent an accurate and faster alternative to the detailed EM and approximate models of loaded microwave cavities [4,5]. Already developed neural models for some applicator configurations [6-8] have verified that neural model with significantly shorter simulation run time provides the same accuracy as detailed EM model. Speed and accuracy in resonant frequency determination are the key issues in the process of experimental characterization of microwave cavities where a great number of measured results has to be compared with numerical results. Therefore, neural models allow an efficient monitoring and identification of resonant modes excited in the experimental cavity under different conditions [1].

Using previously developed neural models of cylindrical metallic cavities of particularly dimension loaded by lossy dielectric slabs [6,7], software package MW-Cavity is developed and presented in this paper. It is intended for efficient determination of resonant frequencies of experimental microwave cavity (Fig.1a), located at the Laboratory for microwave technique and wireless communications at the Faculty of Electronic Engineering in Niš. Current version of presented software provides resonant frequency determination of eight TE$_{mnp}$ and eight TM$_{mnp}$ modes with the lowest resonant frequencies in empty cavity. In addition, MW-Cavity allows for accurate identification of TM/TE$_{mnp}$ modes excited in such cavity.



a) b)

Fig.1. a) Experimental microwave cavity with circular cross-section, b) cylindrical metallic cavity loaded by dielectric slab placed at the cavity bottom

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II. ARCHITECTURE OF MLP MODEL OF CYLINDRICAL METALLIC CAVITY

Fundamental unit of software package MW-Cavity is a library of neural models for the different TE_{mnp} and TM_{mnp} resonant modes that can be excited in a microwave cavity. Each model in the library allows for the resonant frequency calculation of one excited mode. Neural models are developed for the experimental microwave cavity with the following dimensions: $2r$=14 cm and h=14.24 cm, loaded by dielectric slab placed at the cavity bottom (Fig.1b).

For user-selected resonant mode, software package picks up the appropriate neural model from the library with the main task to efficiently calculate the value of resonant frequency for user-defined set of dielectric material parameters. For considered case of experimental microwave cavity, the analyzed parameters of cavity load are dielectric material thickness t (normalized with cavity height giving so-called filling factor $t_h=t/h$) and the real part of relative dielectric permittivity ε_r'. Resonant frequency dependence on these parameters can be expressed with the following function notation:

$$f_r = f(t_h, \varepsilon_r') \qquad (1)$$

This means that neural model, functionally described as $\mathbf{y}=y(\mathbf{x},\mathbf{w})$ where y is a function of appropriate neural network and $\mathbf{w}$ is a weight matrix of neural network [4], will have a vector of input parameters $\mathbf{x}=[t_h, \varepsilon_r']^T$ and a vector of output parameters $\mathbf{y}=[f_r]$. For cavity modeling, the multilayer perceptrons (MLP) neural network is used so that appropriate MLP neural model of cylindrical metallic cavity for this cavity load type is defined as:

$$f_r = y([t_h, \varepsilon'_r]^T, \mathbf{w}) = f_{MLP}(t_h, \varepsilon'_r, W) \qquad (2)$$

where f_{MLP} is a transfer function (or processing function) of the MLP network used for neural model realization. Representing weight matrix $\mathbf{w}$ within one matrix data structure may lead to the difficulties in the process of neural network structure implementation and its training algorithm. Therefore, this matrix is replaced with the set of weight network W whose elements, weight matrices and biases vectors of each neural layer, will be described latter. This replacement has an implementation rather than functional character. During the neural model training, values of weight matrices from W are adjusted in order to bring function f_{MLP} closer as possible to the modeling function (1).

Architecture of MLP neural model of cylindrical metallic cavity loaded by dielectric slab placed at the cavity bottom is shown in Fig.2. Output of l-th hidden layer of MLP network, used for cavity model realization, can be represented by vector $\mathbf{y}_l$ of $N_l \times 1$ dimensions where N_l is a number of neurons in l-th hidden layer. l-th element of this vector, $\mathbf{y}_l[i]$, represents output of i-th neuron of s-th network layer ($s=l+1$ counting also the input layer) $v_i^{(s)}=v_i^{(l+1)}$, i.e. $\mathbf{y}_l = [v_1^{(l+1)}, v_2^{(l+1)}, \ldots, v_{N_l}^{(l+1)}]^T$. It can be shown that this vector is:

$$\mathbf{y}_l = F(\mathbf{w}_l \mathbf{y}_{l-1} + \mathbf{b}_l) \qquad (3)$$

where $\mathbf{y}_{l-1}$ is a $N_{l-1} \times 1$ vector of (l-1)-th hidden layer outputs, $\mathbf{w}_l$ is a $N_l \times N_{l-1}$ connection weight matrix among (l-1)-th and l-th hidden layer neurons and $\mathbf{b}_l$ is a vector containing biases of l-th hidden layer neurons. According to this notation $\mathbf{y}_0$ represents outputs of the buffered input layer $\mathbf{y}_0 = \mathbf{x}$. Element of weight matrix $\mathbf{w}_l$, $\mathbf{w}_l[i,j]$, represents connection weight between i-th neuron in the hidden layer (l-1) and j-th neuron in the hidden layer l, i.e. between i-th neuron in network layer $s=l$ and j-th neuron in network layer $s=l+1$, while element $b_i^{(l)}=\mathbf{b}[i]$ represents a bias value of i-th neuron in the hidden layer l. Function F is the activation transfer function of hidden layer neurons and it can be a logistic sigmoid or hyperbolic tangent sigmoid transfer function [8]. All neurons from the last hidden layer H are connected with the neuron of the output layer. Since the transfer function of output layer is linear, the output of the MLP network is:

$$f_r = \mathbf{w}_o \mathbf{y}_H \qquad (5)$$

where $\mathbf{w}_o$ is a $1 \times N_H$ connection weight matrix among the H-th hidden layer neurons and output layer neuron. Based on this, set of network weights is:

$$W = \{\mathbf{w}_1, ..., \mathbf{w}_H, \mathbf{w}_o, \mathbf{b}_1, ..., \mathbf{b}_H\} \qquad (6)$$

General notation for such defined MLP neural model of cavity is MLPH-N_1-…-N_l-…-N_H where H is a number of the hidden layers of used MLP network, and $N_1,...,N_l,...,N_H$ are numbers of neurons in 1-th,...,l-th,...,H-th hidden layer, respectively. For an example, notation MLP2-12-12 indicates neural network with four neural layers in total (input, output and two hidden layers) and with 12 neurons in the first hidden layer and 12 neurons in the second hidden layer.

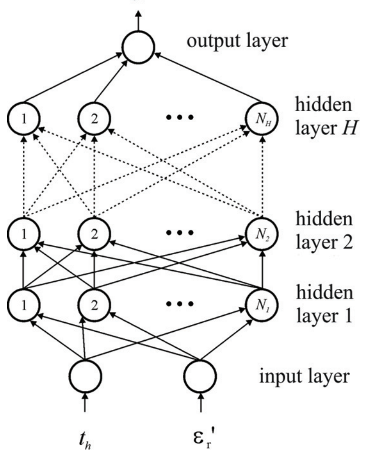


Fig.2. MLP neural model architecture of cylindrical metallic cavity represented in Fig.1

Number of hidden layers in MLP neural network model of loaded cavity as well as the number of neurons in each hidden layer can not be easily predicted. However, there is some rough estimation of number of hidden layers and number of their neurons for which neural model would give satisfying accuracy. Previous researches [6,7] regarding the number of hidden layers in MLP cavity model have shown that at the beginning of modeling process, it is better to chose model with two hidden layers but depending of the training process, that number can be increased or decreased by one. In connection with the number of neurons in the hidden layers, the same researches have indicated that there should be between 6 and 30 neurons in each hidden layer. Therefore, efficient and accurate neural models based on MLP network, developed previously, had the following parameters in the hidden layer structure: $H \in [1, 3]$ and $N_l \in [6, 30]$ for $1 \leq l \leq H$.

III. SOFTWARE PACKAGE MW-CAVITY

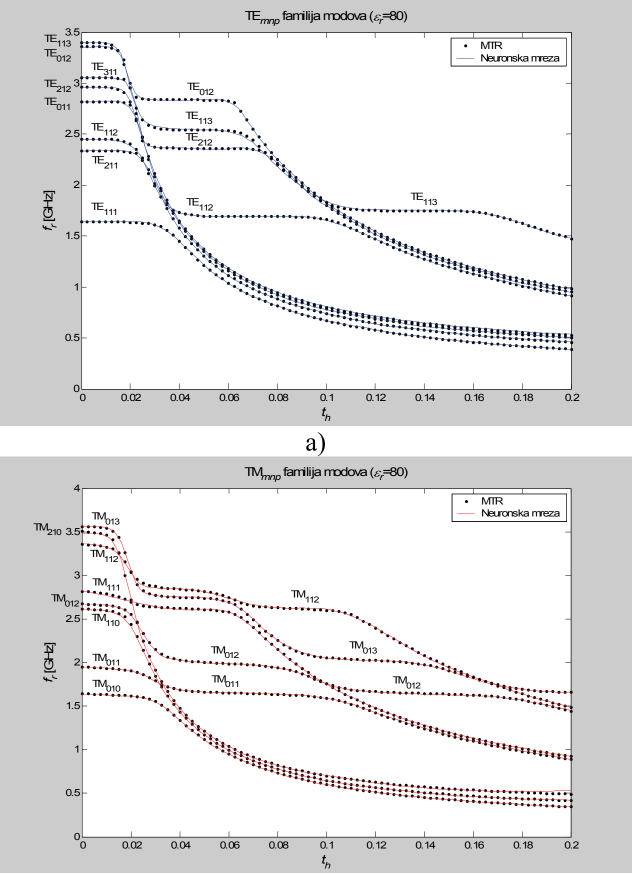
Using MLP models created, according to architecture shown in Fig.2, for different TE_{mnp}/TM_{mnp} resonant modes excited in experimental cavity in Fig.1a, software package MW-Cavity has been developed within Matlab (ver. 6.5) software environment. Package is used for resonant frequency calculation of experimental loaded microwave cavity. For user-chosen values of filling factor and relative dielectric permittivity, MW-Cavity gives, with a high accuracy and high speed, the resonant frequencies of eight TE_{mnp} and eight TM_{mnp} modes with the lowest resonant frequencies in empty cavity.

Training of each MLP model, integrated within MW-Cavity software package and associated to appropriate TM/TE_{mnp} mode, has been done with 1640 uniformly distributed training samples. Influence of dielectric losses changes on resonate frequency has been disregarded so that complex relative dielectric permittivity $\underline{\varepsilon_r} = \varepsilon_r' - j\varepsilon_r''$ is determined using fixed losses: $\varepsilon_r''/\varepsilon_r'=0.07$. Input parameters of MLP model and their ranges were: $1 \leq t_h \leq 3$ i $2 \leq \varepsilon_r' \leq 82$. In order to obtain model with better accuracy, at the first stage, for each resonant mode training of several different MLPH-N_1-…-N_l-…-N_H ($1 \leq H \leq 3$ i $6 \leq N_l \leq 30$) models on the same training set has been done. At the second stage, based on results obtained using testing set (different from the training set), the model with the smallest average testing error is incorporated into software package. MLP models integrated within MW-Cavity software package and their testing results are shown in Table 1.

TABLE 1. CHOSEN MLP MODELS FOR TE/TM RESONANT MODES, INCORPORATED INTO MW-CAVITY SOFTWARE AND THEIR TESTING RESULTS

Mode	Model	Worst case error [%]	Average error [%]
TE_{111}	MLP2-10-9	1.74	0.27
TE_{211}	MLP2-12-12	2.72	0.23
TE_{112}	MLP2-10-10	2.21	0.29
TE_{011}	MLP2-15-15	2.52	0.23
TE_{212}	MLP2-20-10	2.16	0.24
TE_{311}	MLP2-17-9	2.34	0.35
TE_{012}	MLP2-20-20	1.81	0.24
TE_{113}	MLP2-20-20	2.18	0.27
TM_{010}	MLP2-12-10	1.04	0.23
TM_{011}	MLP2-18-16	1.87	0.38
TM_{110}	MLP2-8-8	1.33	0.26
TM_{012}	MLP2-20-10	1.41	0.32
TM_{111}	MLP2-12-12	1.76	0.26
TM_{112}	MLP2-12-11	1.64	0.35
TM_{210}	MLP2-12-8	1.57	0.29
TM_{013}	MLP2-22-18	1.99	0.22

As an illustration of MW-Cavity capabilities, the values for resonant frequency of experimental microwave cavity loaded partially by water dielectric slab, obtained by this software are shown in Figs.3-4. It can be seen a good agreement between MW-cavity results and results obtained by using TRM. Calculation of resonant frequency in 100 points of filling factor for all supported model lasted below 1 sec which verifies the speed of implemented neural models.

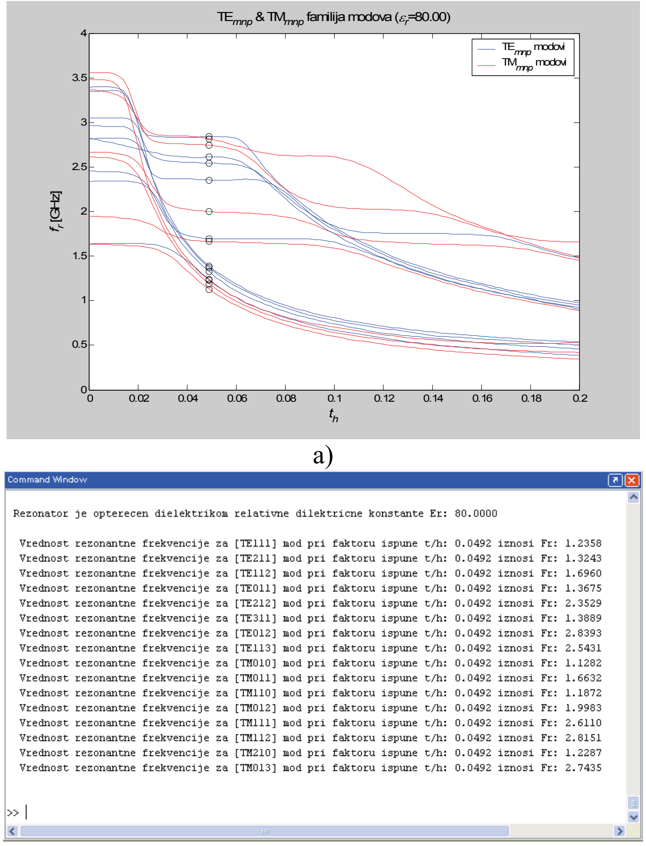


a)

b)

Fig.3. Comparison of resonant frequencies of experimental cavity for a) TE_{mnp} modes and b) TM_{mnp} modes, obtained using software MW-Cavity and TRM for the case of relative dielectric permittivity ε_r' =80 (water)

For a complete EM characterization of microwave applicators, identification process of excited resonant modes is required. Identification process detects which TE/TM mode is excited in the cavity for a given value of filling factor. Such process usually requires resonant frequency determination in a greater number of points by using S_{11} reflection measurements in a wide range of filling factor change and comparison of measured resonant frequency results with referent values for TE/TM modes that can be excited. Owing to previously verified capabilities, MW-Cavity software package can increase an efficiency of identification process as it is capable to generate, in a very short time interval, a great number of referent data needed for detection and following of excited resonant modes. Resonant frequencies obtained by reflection measurement in the experimental cavity are shown in Fig. 5, while Table 2 presents comparison of resonant frequency results obtained by MW-Cavity and measurement procedure for modes whose referent values have a very good agreement with measurements. Such modes are modes candidates for identification but in order to verify this assumption, agreement between measured and referent resonant frequency values has to be confirm in a wide range of filling factor change.



a)

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Rezonator je opterecen dielektrikom relativne dilektricne konstante Er: 80.0000

 Vrednost rezonantne frekvencije za [TE111] mod pri faktoru ispune t/h: 0.0492 iznosi Fr: 1.2358
 Vrednost rezonantne frekvencije za [TE211] mod pri faktoru ispune t/h: 0.0492 iznosi Fr: 1.3243
 Vrednost rezonantne frekvencije za [TE112] mod pri faktoru ispune t/h: 0.0492 iznosi Fr: 1.6960
 Vrednost rezonantne frekvencije za [TE011] mod pri faktoru ispune t/h: 0.0492 iznosi Fr: 1.3675
 Vrednost rezonantne frekvencije za [TE212] mod pri faktoru ispune t/h: 0.0492 iznosi Fr: 2.3529
 Vrednost rezonantne frekvencije za [TE311] mod pri faktoru ispune t/h: 0.0492 iznosi Fr: 1.3889
 Vrednost rezonantne frekvencije za [TE012] mod pri faktoru ispune t/h: 0.0492 iznosi Fr: 2.8393
 Vrednost rezonantne frekvencije za [TE113] mod pri faktoru ispune t/h: 0.0492 iznosi Fr: 2.5431
 Vrednost rezonantne frekvencije za [TM010] mod pri faktoru ispune t/h: 0.0492 iznosi Fr: 1.1282
 Vrednost rezonantne frekvencije za [TM011] mod pri faktoru ispune t/h: 0.0492 iznosi Fr: 1.6632
 Vrednost rezonantne frekvencije za [TM110] mod pri faktoru ispune t/h: 0.0492 iznosi Fr: 1.1872
 Vrednost rezonantne frekvencije za [TM012] mod pri faktoru ispune t/h: 0.0492 iznosi Fr: 1.9983
 Vrednost rezonantne frekvencije za [TM111] mod pri faktoru ispune t/h: 0.0492 iznosi Fr: 2.6110
 Vrednost rezonantne frekvencije za [TM112] mod pri faktoru ispune t/h: 0.0492 iznosi Fr: 2.8151
 Vrednost rezonantne frekvencije za [TM210] mod pri faktoru ispune t/h: 0.0492 iznosi Fr: 1.2287
 Vrednost rezonantne frekvencije za [TM013] mod pri faktoru ispune t/h: 0.0492 iznosi Fr: 2.7435


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b)

Fig.4. Calculation of resonant frequencies of experimental cavity for TE$_{mnp}$/TM$_{mnp}$ modes obtained using software MW-Cavity for filling factor t_h=0.0492 (t=7 mm) and ε_r'=80 (water):
a) TE$_{mnp}$/TM$_{mnp}$ resonant frequency curves shown in user window, b) values of some resonant frequencies shown in user window

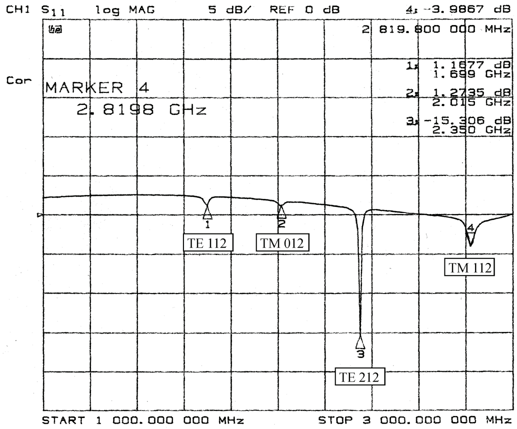

Fig.5. Resonant frequencies obtained by reflection measurement in the experimental cavity for filling factor t_h = 0.0492 (t=7 mm)

Table 2. Comparison of resonant frequency results obtained by software MW-Cavity and measurement procedure

Measured values [GHz]	1.699	2.015	2.350	2.820
MW-Cavity [GHz]	1.696	1.998	2.353	2.815
Mode candidate for identification	TE$_{112}$	TM$_{012}$	TE$_{212}$	TE$_{112}$

IV. CONCLUSION

Neural network models, as a good alternative to EM models of loaded microwave cavities, have the same simulation speed as approximate model [3] and the accuracy very close to the detailed EM models. It is shown that for a sufficient number of a neural model training samples, multilayer perceptrons network can very successfully model the dependence of excited modes resonant frequency as a function of dielectric slab parameters

Developed architecture of MLP cavity model is used for a realization of library of neural models for different TE$_{mnp}$/TM$_{mnp}$ modes that can be excited in experimental microwave cavity. This library is integrated in the software package MW-Cavity developed within Matlab environment. Application of developed software for resonant frequency determination of experimental cylindrical cavity loaded by water dielectric slab has produced the results of a high agreement with EM results within a few order of magnitude faster simulation run time than detailed EM models.

In addition, software package MW-Cavity" is used in the identification process of resonant modes excited in loaded cavity. Such process usually requires that for a very short time interval and for a wide range of cavity filling factor changes, a great number of calculations of resonant frequencies have to be performed in order to follow and identify different excited modes. MW-Cavity software has successfully met all these requirements, allowing for efficient resonant modes identification.

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