3D electron beam distribution estimation by neural models

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Abstract: *The electron beam technological processes like electron beam welding, electron beam additive technologies, etc. depend strongly on the characteristics of the electron beam, generated by the electron gun. In this work the estimation of the 3D radial current density distribution using training, testing and validation of different artificial neural networks is considered. The model estimation is based on experimental measurements of the electron beam current distribution in three cross-sections of the beam at different distances from the magnetic lens of the electron gun. The estimated neural models with different structures are compared. Graphical user interface for the evaluation of the radial electron beam distribution in any cross-sections of the beam is developed.*
Keywords*: ELECTRON BEAM CURRENT DISTRIBUTION, GRAPHICAL USER INTERFACE, NEURAL NETWORK MODELS.*

1. Introduction

The electron beam technological processes like electron beam welding, electron beam additive technologies, etc. depend strongly on the characteristics of the electron beam, generated by the electron gun. The characterization of the electron beam is one of the necessary conditions for the transfer of technologies from one equipment to another, as well as for the comparison of the quality of different electron beam facilities (guns).

The knowledge of the radial current distribution in different beam cross-section planes is the first step in the electron beam characterization [1 - 3]. It helps the determination of the crossover (focus) position. Better understanding for the electron beam/work-piece interaction along the beam penetration depth and the ability for its prognostication are defined by the simultaneous evaluation of radial and angular distribution of the beam electrons. The electron beam emittance [4] is a suitable parameter for standardization of the electron optical technology systems, which can be calculated applying the estimated parameters of the radial and the angular distributions of the beam. The evaluation of this parameter is a key condition for achieving good quality, repeatability and reproducible performance of electron beam welds. The emittance strongly influences the ability of the electron beam to penetrate into the processed material and directly determines the maximal depth of the welded joints, obtained by electron beam welding. This parameter forms the basis for transferring a concrete technology from one machine to another which will minimize the volume of preliminary experimental tests to adjust the process parameters as well as will extend the capability of the expert systems to define the process parameter settings during welding (or other processing) of different materials.

In this work the estimation of the 3D radial current density distribution using training, testing and validation of different artificial neural networks is considered. The model estimation is based on experimental measurements of the electron beam current distribution in three cross-sections of the beam at different distances from the magnetic lens of the electron gun. The estimated neural models with different structures are compared. Graphical user interface for the evaluation of the radial electron beam distribution in different cross-sections of the beam is developed.

2. Experimental conditions

The electron beam spot is analyzed in three cross sections by implementation of the beam current point by point measurement in 100 points (10×10) in each cross-section. This number of points, if they are small enough, is sufficient to determine several peaks (three-dimensional formations in 3D current distribution diagrams (Fig. 1). The total measurement time of the selected number of tested points – 100 – is approximately equal to for 20 s and the total time to determine the value of current density at one point is 140 ms.

The procedure for measuring the current in a given position of the plates (*x*, *y*) is the following:

a) measuring the current collected by the Faraday cylinder; this happens in about 15 ms. During this time, this current is measured 10 - 30 times and its average value is calculated and stored in computer memory;

b) the electron beam is defocused and deflected on a powerful energy collector;

c) the analytical plate is moved to the next position. Eventually, the first protective plate is moved at the same time, if all measurements at a given position have been made;

d) the electron beam is returned to the measuring position at the focus at which the beam is examined. The time to establish the normal focus of the beam (and distribution in the steady beam) is of the order of 15 ms.

After that the measuring the current of the Faraday cylinder at the new position of the new point is repeated from point a).

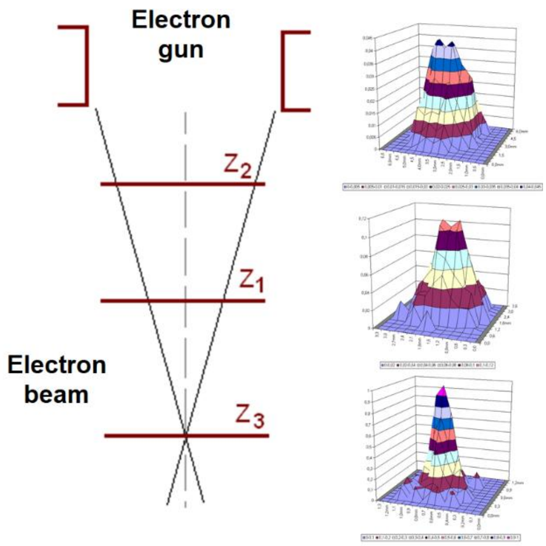


Fig. 1 *Measured electron beam current distributions in three cross-sections of the beam: z_1 = 245 mm, z_2 = 170 mm and z_3 = 320 mm from the end of the focusing coils of the electron gun.*

The data on the current density distributions *j*(*x*, *y*) are obtained in three beam sections at distances: z_1 = 245 mm, z_2 = 170 mm and z_3 = 320 mm from the end of the focus coils. The parameters of the electron beam are: beam power 2.4 kW, beam current 40 mA and accelerating voltage 60 kV. At a distance of z_3 = 320 mm is found the crossover of the electron beam.

3. Neural Networks

Neural networks (NN) are universal approximators with low sensitivity to errors, which determines the benefits of their use in different application areas [5, 6].

For developing an expert system for defining the electron beam current density distribution an input-output structure of the neural network-based model is used, i.e. the neural network consists of 3 input neurons, hidden layer (with different number of neurons), and 1 output neuron.

The methodology, implemented for developing of neural network models, consists of the following general steps:

- Selecting the type and structure of the NN model structure.
- Training of the created NN by using the back-propagation method experimentally obtained (and/or numerically simulated) set of training data to a satisfactory accuracy [5, 7, 8].
- Choosing the neural network model structure.
- Recall of the trained neural network for prediction, investigation and parameter optimization.

For comparison of the neural network models the mean squared error (MSE) (1), as well as the regression multiple correlation coefficient R (2) are calculated:

$$MSE = \frac{\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}{n}, \tag{1}$$

$$R = \sqrt{1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{\bar{y}})^2}}, \tag{2}$$

where $\hat{y}$ and y is the predicted and the experimental values, $\bar{\bar{y}}$ is the overall average of all mean values, and n is the number of data.

For training, validation and testing of the neural networks, the experimental data are randomly separated into 3 parts: 70 % (506 datasets) for training, 15 % (108 datasets) for validation and 15 % (108 datasets) for testing.

3.1. Feedforward neural network

Feedforward neural network consists of a series of layers. The first layer has a connection from the network input. Each subsequent layer has a connection from the previous layer. The final layer produces the network's output.

Feedforward networks can be used for any kind of inputs to output mapping. A feedforward network with one hidden layer and enough neurons in the hidden layers can fit any finite input-output mapping problem. Two-layer feed-forward network with sigmoid hidden neurons and linear output neurons is presented in Fig. 2. The network is trained with Levenberg-Marquardt backpropagation algorithm [6, 8].

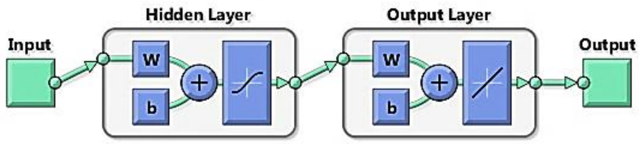


Fig. 2 *Feedforward neural network structure*

Matlab environment is used to implement the described approach for training NN with different structures of the hidden layer – with 3, 5, 10 and 15 hidden units and different random sets for training (506 datasets), for validation (108 datasets) and for testing (108 datasets). The best four Neural network models, based on the experimental observations are chosen.

The obtained results for the accuracy of the training, validation and testing of these four NN models are presented in Table 1 – Table 3 correspondently.

Table 1. *Feedforward neural network training results*

	NN with 3 hidden neurons	*NN with 5 hidden neurons*	*NN with 10 hidden neurons*	*NN with 15 hidden neurons*
MSE	0.007784	0.003978	0.001244	0.002359
R	0.5245	0.683	0.8182	0.8595

Table 2. *Feedforward neural network validation results*

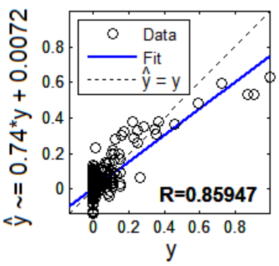
	NN with 3 hidden neurons	*NN with 5 hidden neurons*	*NN with 10 hidden neurons*	*NN with 15 hidden neurons*
MSE	0.001902	0.0104	0.004465	0.004205
R	0.6927	0.6449	0.7561	0.8708

Table 3. *Feedforward neural network testing results*

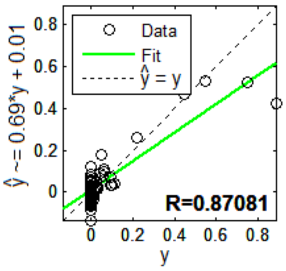
	NN with 3 hidden neurons	*NN with 5 hidden neurons*	*NN with 10 hidden neurons*	*NN with 15 hidden neurons*
MSE	0.00611	0.00456	0.01616	0.002229
R	0.6165	0.7704	0.8719	0.8198

From the tables it can be seen, that from these four structures better results are obtained by using the neuron network models with a hidden layer, consisting from 15 hidden neurons, due to the smaller values of MSE and closer to 1 values of the coefficient R, obtained during training, validation and testing stages.

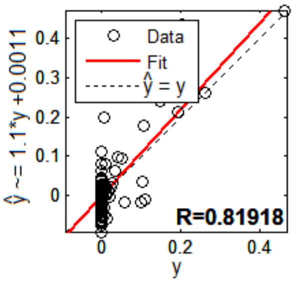
The NN whit 15 hidden neurons training, validation and testing results from accuracy cross-validations for the electron beam current distribution estimation are presented in Fig. 3.



a) training



b) validation



c) testing

Fig. 3 *Feedforward neural network whit 15 hidden neurons: a) training, b) validation and c) testing results for defining the electron beam current density distribution.*

4. Expert System

Matlab environment is used to develop a Graphical user interface (GUI), shown in Fig. 4, which represents a part of an expert system for decision making for the management and control of the electron beam.

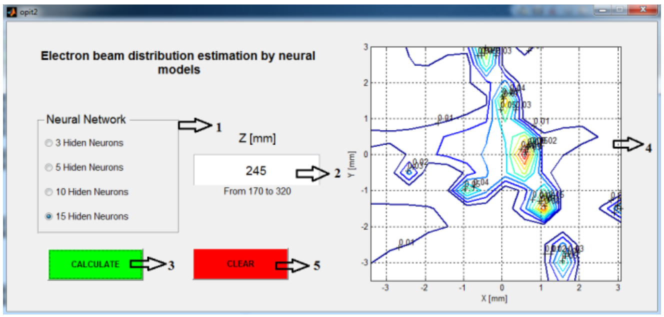


Fig. 4 *Graphical user interface for 3D electron beam distribution estimation.*

In Fig. 4 it can be seen that the developed Graphical user interface for 3D electron beam radial current distribution estimation has a radio-button section “1” for the choice of the structure of the Neural network model with several options for the user:

- Neural Network with 3 hidden neurons;
- Neural Network with 5 hidden neurons;
- Neural Network with 10 hidden neurons;
- Neural Network with 15 hidden neurons.

Once the desired structure of the neural model has been selected, a value must be entered in field “2”, within the limits indicated below the field (from 170 to 320 mm) for the distance of the beam cross-section from the end of the focusing coils of the electron gun.

By pressing the "Calculate" button “3”, the necessary calculations are initialized with the selected neural network model “1” and the value entered in field “2”.

Prior to the calculation for the estimation of the electron beam current distribution, the expert system checks whether the input parameter “2” is correct and whether it falls within the specified limits. If the check concludes that the entered value is incorrect, a message in the field “4” inviting the user to enter a valid value (Fig. 5) is displayed. If the input value passes the check and it is in considered region, the calculation continues with the chosen neural network model and result is graphical presentation of the contour plot, shown in field “4”.

There is a function in Fig. 4 presented by button “5” or “Clear”. Pressing this button, the program clears all data from fields “2” and “4” and the expert system is ready for the next calculation.

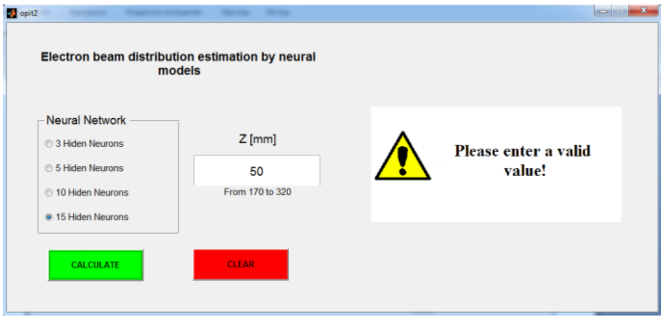


Fig. 5 *Error message for the incorrect input value.*

5. Conclusions

In this work presents the results from the estimation of the 3D radial current density distribution using training, testing and validation of different artificial neural networks. The model estimation is based on experimental measurements of the electron beam current distribution in three cross-sections of the beam at different distances from the magnetic lens of the electron gun. The estimated neural models with different structures are compared. Matlab environment is used to develop a Graphical user interface (GUI) for 3D radial current density distribution calculation, which represents a part of an expert system for decision making for the management and control of the electron beam.

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