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Neutron spectrometry using artificial neural networks for a bonner sphere spectrometer with a ^{3}He detector

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Neutron spectra unfolding and dose equivalent calculation are complicated tasks in radiation protection, are highly dependent of the neutron energy, and a precise knowledge on neutron spectrometry is essential for all dosimetry-related studies as well as many nuclear physics experiments. In previous works have been reported neutron spectrometry and dosimetry results, by using the ANN technology as alternative solution, starting from the count rates of a Bonner spheres system with a ^{6}LiI(Eu) thermal neutrons detector, 7 polyethylene spheres and the UTA4 response matrix with 31 energy bins. In this work, an ANN was designed and optimized by using the RDANN methodology for the Bonner spheres system used at CIEMAT Spain, which is composed of a ^{3}He neutron detector, 12 moderator spheres and a response matrix for 72 energy bins. For the ANN design process a neutrons spectra catalogue compiled by the IAEA was used. From this compilation, the neutrons spectra were converted from lethargy to energy spectra. Then, the resulting energy ?uence spectra were re-binned by using the MCNP code to the corresponding energy bins of the ^{3}He response matrix before mentioned. With the response matrix and the re-binned spectra the counts rate of the Bonner spheres system were calculated and the resulting re-binned neutrons spectra and calculated counts rate were used as the ANN training data set.

Keywords: Neutron spectrometry; neutron dosimetry; neural networks.

La reconstrucción de espectros de neutrones y el cálculo de los equivalentes de dosis dependen de la energía de los neutrones, y por ello es esencial un conocimiento preciso de la espectrometría de los neutrones para realizar los estudios relacionados con la disimetría, así como para la realización de muchos experimentos de la física nuclear. Estos no son problemas triviales y los investigadores han mencionado la necesidad de desarrollar técnicas de medición adicionales para ampliar los actuales sistemas de monitoreo del personal laboral. En trabajos previos se han reportado resultados relacionados con la espectrometría y la disimetría de neutrones, utilizando la tecnología de redes neuronales como solución alternativa a partir de las tasas de conteo de un sistema de esferas Bonner con un detector de neutrones térmicos de ^{6}LiI(Eu), 7 esferas de polietileno y la matriz de respuesta conocida como UTA4, expresada en 31 grupos de energía. En este trabajo, se diseño y optimizo una red neuronal para el sistema de esferas Bonner del CIEMAT en España, utilizando la metodología de diseño conocida como RDANN, el cual esta compuesto de un detector de neutrones térmicos de ^{3}He, 12 esferas moderadoras y una matriz de respuesta expresada en 72 grupos de energía. Para el proceso de diseño de la red neuronal se utilizó un catalogo de espectros de neutrones compilado por la IAEA. A partir de esta compilación, los espectros de neutrones se convirtieron de letargia a energía. Posteriormente, éstos espectros se rebobinaron utilizando el código MCNP de acuerdo con los grupos de energía de la matriz de respuesta del detector de ^{3}He. Con la matriz de respuesta y los espectros rebobinados se calcularon las tasas de conteo del sistema de esferas Bonner y de esta forma, los espectros rebobinados resultantes y las cuentas calculadas se utilizaron como el conjunto de datos de entrenamiento de la red neuronal.

Descriptores: Espectrometría de neutrones; dosimetría de neutrones; redes neuronales.

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1. Introduction

Neutron energy spectra found in workplaces are often complex, the range of neutron energies involved can extend over nine or ten orders of magnitude. To improve the assessment of personal equivalent dose (Hp) and ambient dose equivalent ($H^*(10)$) in workplace, requires the proper characterization of neutron spectra [1]. The monitoring of occupational radiation exposure in neutron fields is mainly done with multi-element systems where each element has a particular response to neutrons. With the neutron spectrum information and neutron fluence-to-dose conversion coefficients, different dose quantities, like Hp or $H^*(10)$, can be estimated.

With the Bonner spheres spectrometer (BSS), neutron spectrum from thermal to several MeV can be obtained.

However, the weight, time consuming procedure, the need to use an unfolding procedure and the low resolution spectrum are some of the BSS drawbacks. The BSS response matrix, the count rates and the neutron spectrum are related through the Fredholm integral-diferential equation, whose discrete version is.

$$C_j = \sum_{i=1}^{N} R_{i,j}\Phi_i \quad j = 1, 2, \ldots, m \tag{1}$$

where C_j is j^{th} detector's count rate; $R_{i,j}$ is the j^{th} detector's response to neutrons at the i^{th} energy interval; Φ_i is the neutron fluence within the i^{th} energy interval and m is the number of spheres utilized.

Equation 1 is an ill-conditioned equations system with an infinite number of solutions. To unfold the neutron spectrum, Φ, several methods are used [1]. The ANN technology is a useful alternative to solve this problem; however, several drawbacks must be solved in order to simplify the use of these procedures [2]. In the ANN design process, the choice of the ANN's basic parameters often determines the success of the training process. The selection of these parameters follows in practical use no rules, and their value is at most arguable. The ANN designers have to choose the architecture and determine many of the parameters through the trial and error technique, which produces ANN with poor performance and low generalization capability, spending often large amount of time. In the aim to solve these drawbacks, a new approach known as Robust Design of Artificial Neural Networks (RDANN) methodology has been proposed [2]. In this work, an ANN was designed and optimized by using the RDANN methodology for the BSS utilized by the "Laboratorio de Metrología de Radiaciones Ionizantes" (LMRI) of CIEMAT at Spain.

2. Materials and methods

CIEMAT's BSS system is composed of a ^{3}He neutron detector, 12 moderator spheres and a response matrix. In this work, the selected response matrix it is expressed for 72 energy bins. For the ANN design process a catalogue of neutron spectra compiled by the International Atomic Energy Agency (IAEA) was used [3]. These include spectra from isotopic neutron sources, reference and operational neutron spectra obtained from accelerators and nuclear reactors, and spectra obtained from mathematical functions. From this compilation, the neutron spectra were converted from lethargy to energy spectra. Then, the resulting energy fluence spectra were re-binned by using the MCNP code to the corresponding energy bins of the CIEMAT's BSS system, and 13 equivalent doses were calculated in the re-binning process [3].

Re-binned spectra were normalized to 1 neutron per second and the expected count rates in the Bonner sphere spectrometer were calculated using the CIEMAT response matrix. The count rates were utilized as inputs in the network, while the respective neutron spectrum and equivalent doses were utilized as the output, during the training and testing stages. For the ANN design process, the net topology should be determined, however, many factors affect the ANN performance. Over the past years, new proposals of ANN design procedures have been made, because the serious drawbacks due to the trial and error technique. Recently, a novel approach known RDANN methodology, has been applied in the design process of ANN. RDANN methodology is a powerful method based on parallel processes, where all the experiments are planned a priori, and the results are analyzed after all experiments are completed. This is a systematic and methodological approach of ANN design, based on statistical methods, which maximize the ANN performance and their generalization capacity.

In this work, a multilayer feed forward backpropagation ANN with momentum and learning rate was designed. Using the RDANN methodology, the ANN was designed and optimized to solve 14 independent problems: the neutron spectra unfolding problem and the calculation of 13 different equivalent doses, starting only from the count rates of the CIEMAT's BSS system.

3. Results and discussion

The optimum network topology is 12:16:85, momentum: 0.001, learning rate: 0.1, training algorithm: trainscg, target MSE: 1e-4. The first layer (input) are the count rates readed from the CIEMAT's BSS, the second layer (hidden) has 16 neurons and the thirth layer (output) has 85 neurons. The first 72 outputs correspond to the neutron spectra, as is showed in Fig. 1, and the remaining 13 are equivalent doses, (Fig. 2). Training was carried using 200 spectra, randomly selected from the whole data set, and the remaining were used for testing the learning of the net. The neural net was trained until the mean square error (MSE) was reduced to 10^{-4}, in a time of 107 seconds average.

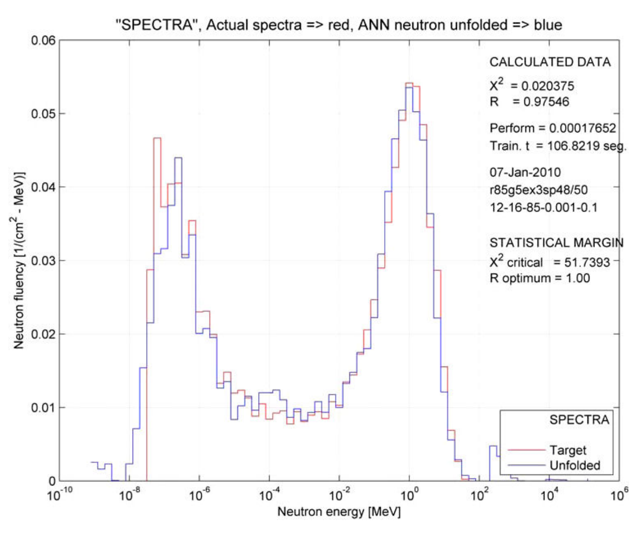

FIGURE 1. Neutron spectra unfolded with the optimized ANN.

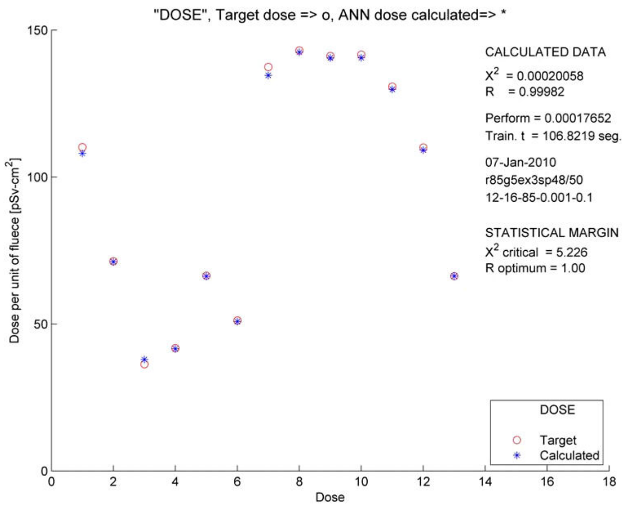

FIGURE 2. 13 equivalent doses calculated with the optimized ANN.

Opposite to classical solution methods, in the ANN approach, the count rates comming from a BBS system are the only input data, not being necessary initial guess spectrum. The neutron spectra is unfolded and simultaneously, 13 equivalent doses are calculated. The equivalent doses, are not dependent of the spectrometric information, they are calculated simulteneously, based only on the BSS counts. Figs. 1 and 2 shown the results of one case obtained at the testing stage of the designed ANN. Figure 1 shows the expected neutron spectra (red line) and the calculated by the ANN (blue line). Similarly, Fig. 2, shows the 13 doses. The RDANN methodology makes statistical tests as χ^2 and correlation in order to analyze the performance and generalization capabilities of the network.

From Figs. 1 and 2 can be seen that according the RDANN methodology, the expected an obtained spectra and doses pass the χ^2 test, which means that statistically both, spectra and doses, are the same. From these figures can be seen too, that the correlation test is close to the best value. This means that this network topology has a high performance and generalization capability.

4. Conclusions

The use of ANN technology is a useful alternative to solve the neutron spectrometry and dosimetry problems; however, to obtain the best results, some drawbacks must be solved in the ANN design process, such as the optimum ANN topology selection. In this work, the ANN optimization methodology known as RDANN, was used to design an ANN capable to solve the neutron spectrometry and dosimetry problems for the CIEMAT BSS system.

The neural net was trained and tested using a large set of neutron spectra compiled by the IAEA. The success of ANN technology in neutron spectrometry and dosimetry, using only the Bonner spectrometer count rates as input in the trained network will overcome some of the the problems associated with the solution of such ill-conditioned problem. The results here reported demonstrate that the use of this technology has become in a useful tool.

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