Abstract: Conductive silicone rubber has great advantages for strain sensing applications. The electrical behavior of the elastomeric material is rate-dependent and exhibit hysteresis upon cyclic loading. Several constitutive models were developed for mechanical simulation of this material upon loading and unloading. One of the successful approaches to model the time-dependent behavior of elastomers is Bergstrom-Boyce model. The paper summarizes the results of investigations on the conductive silicone rubber as strain sensor. An experimental investigation of the sensors subjected to different time-dependent strain histories is presented. Three different tests have been developed to measure time-dependent and strain-dependent behavior of the rubber. To investigate the electrical properties, the resistance of silicone was measured during the mechanical tests. An adaptive neuro-fuzzy inference system (ANFIS) is used to approximate correlation between these measured features of the material and to predict its unknown future behavior. ANFIS has unlimited approximation power to match any nonlinear function arbitrarily well on compact set and to predict a chaotic time series.

Key words: conductive silicone rubber, adaptive neuro fuzzy, prediction, strain sensor

1. INTRODUCTION

Artificial neural networks (ANNs) are flexible modeling tools with capabilities of learning the mathematical mapping between input and output variables of nonlinear systems. One of the most powerful types of neural network system is adaptive neuro fuzzy inference system (ANFIS). ANFIS shows very good learning and prediction capabilities, which makes it an efficient tool to deal with encountered uncertainties in any system. Fuzzy Inference System (FIS) is the main core of ANFIS. FIS is based on expertise expressed in terms of ’IF–THEN’ rules and can thus be employed to predict the behavior of many uncertain systems. FIS advantage is that it does not require knowledge of the underlying physical process as a precondition for its application. Thus ANFIS integrates the fuzzy inference system with a back-propagation learning algorithm of neural network. An ANFIS model has been established in this study to predict the voltage changing of conductive silicone rubber during compression tests. The experimental results were obtained from many compression strain tests to make accurate representation of the material behavior.

In this study, based on our experimental measurements, an constitutive model was developed. This model was made by using ANFIS. So far, experimental investigation of mechanical and electrical properties of conductive silicone rubber was performed in [1]. There are many studies of the application of ANFIS for prediction and real-time identification of many different systems. In [2] the effectiveness of predicting non-uniformity of the wafer surface with ANFIS was investigated under conditions of the three process parameters. A developed finite element method was used to obtain the training data and testing data about non-uniformity on wafer surface.

An ANFIS model is developed in [3] to forecast the energy requirements of different types of buildings having different properties. A neuro-fuzzy model was utilized to predict the hardness and porosity of shape memory alloy in [4]. The purpose of that study is estimation of porosity and hardness of the produced samples. Paper [5] presented an improved ANFIS with self-feedback for the applications of time-series prediction. An ANFIS model is applied to predict the flow stress in hot deformation process of Ti6000 alloy in [6]. In [7] optimum cure time of the rubber compounds are predicted using ANFIS model. Various principles of the neural network approach for predicting certain properties of polymer composite materials are discussed in [8]. The applicability of ANFIS for prediction of carbon dioxide solubility in polymers was showed in [9]. In paper [10] was developed a micromechanism theory that successfully captures many of the time-dependent characteristics of filled rubber.

An ANFIS model will be established in this study to predict the voltage changing of conductive silicone rubber during compression tests. Many compression tests of conductive silicone rubber has been conducted at different strain rates and strains to characterize the voltage changing behavior and understand the deformation mechanisms during the deformation process. The constructed ANFIS model exhibits a high performance for predicting voltage changing of the conductive silicone rubber during compression tests. The results obtained in this work indicate that ANFIS is effective method for prediction of voltage changing in conductive silicone rubber and have better accuracy and simplicity compared with the classical methods.
2. MATERIAL AND METHOD

2.1. Experimental Measuring

The carbon-black filled silicone rubber is electrically conductive and its resistance changes by deformation. These properties make this material suitable to develop force or deformation sensors. The characteristics of voltage and stress were represented as function of deformation and time. Various compression tests of the silicone were performed. The specimens were made by press-curing from carbon-black filled silicone rubber (Elastosil R570/70, Shore A 70), as shown in Figure 1. The changing of electrical resistance of silicone rubber specimens were measured with the help of special compression tool and electrodes vulcanized on the top bottom side of the specimens. Measurement electrode was cured on those sides of silicone rubber specimens. The electrodes were made from soft copper weave since it makes good electrical contact. Wires were soldered on the electrodes with connectors to connect to the measurement instrument.

![Fig.1. Raw conductive silicone rubber Elastosil R570/70 and one cubic sensor-specimen](image1)

Zwick ProLine material-testing machine Z005, shown in Figure 2, was used to measure the mechanical and electrical properties of the sensor-elements. Throughout the mechanical tests, the resistance-deformation and force-deformation diagrams were recorded and automatically drawn via the software testXpert II. As input voltage for electrical source 5V were used according to initial resistance of the sensor-elements during the compression test.

![Fig.2. Experimental setup for ProLine material-testing machine](image2)

2.2. Adaptive Neuro Fuzzy Inference System

Adaptive neuro fuzzy system (ANFIS) was suggested by Jang [11]. ANFIS can serve as a basis for constructing a set of fuzzy ‘if-then’ rules with appropriate membership function to generate the stipulated input-output pairs. The membership functions are tuned to the input-output data. ANFIS is about taking an initial fuzzy inference (FIS) system and tuning it with a back propagation algorithm based on the collection of input-output data. The basic structure of a fuzzy inference system consists of three conceptual components: a rule base, which contains a selection of fuzzy rules; a database, which defines the membership functions used in the fuzzy rules; and a reasoning mechanism, which performs the inference procedure upon the rules and the given facts to derive a reasonable output or conclusion. These intelligent systems combine knowledge, technique and methodologies from various sources. They possess human-like expertise within a specific domain – adapt themselves and learn to do better in changing environments. In ANFIS, neural networks recognize patterns, and help adaptation to environments. Fuzzy inference systems incorporate human knowledge and perform interfacing and decision-making.

Here the training data is obtained by many compression tests of the silicone specimens. One half of the data are used for training while the other half is used for checking and validation of the model. With a proper training scheme and fine filtered data-sets, ANFIS is capable of predicting voltage values quite accurately since it learns from training data. This measurement-free architecture also makes it immediately available for operation once they are trained.

In time series prediction the past values of voltage changing up to time “t” are used to predict the value at some point in the future “t+p”. The standard method for this type of prediction is to create a mapping from D points of the time series spaced “Δt” apart; that is \[ x(t-\Delta t), x(t-2\Delta t), \ldots, x(t-D\Delta t) \] to predict a future value \( x(t+p) \), where \( D = 4 \) and \( \Delta = p = 6 \) are used. For off-line learning data is updated and predicted only after presentation of entire data set, or only after an epoch. The number of times the entire data set is used to check and validate the prediction is called epoch number. Matlab’s Fuzzy logic toolbox is used for the entire process of training and evaluation of FIS.

In order to build an ANFIS that can predict \( x(t+p) \) from the past values of voltage changing, the training data format is \[ \{x(t-\Delta t), x(t-2\Delta t), x(t-6), x(t), x(t+6), x(t+12), x(t+18)\} \]. As can be seen, there are four inputs and one output. The inputs are \( x(t-\Delta t), x(t-2\Delta t), x(t-6), x(t) \) and the output is \( x(t+6) \). There are two membership functions on each input since this structure has fast training procedure. In this study we have chosen bell-shaped membership functions with maximum equal to 1 and minimum equal to 0. This type of functions has best characteristics for fuzzing the inputs. Experimental results of voltage changing are shown in Figure 3. To avoid slow training procedure, the experimental data were trimmed. The first 10 seconds of the data are ignored to avoid the transient portion of the data. Training and checking data are shown.
in Figure 4 and input bell-shaped membership functions for training are shown on Figure 5. One half of the data are used for training while the other is used for checking and therefore the number of rules is $2^4=16$ rules. In the generating FIS matrix the number of fitting parameters is 104, including 24 non-linear parameters and 80 linear parameters. Most of the fitting is done by the linear parameters. The non-linear parameters are mostly used for fine tuning for further improvement. We applied the hybrid learning algorithms to identify the parameters in the ANFIS architectures. This algorithm has a forward and a backward pass which results in very good and fast learning error decresing.

![Voltage changing curve](image)

**Fig.3. Voltage changing curve from experimental measurements**

![Voltage changing curve for ANFIS](image)

**Fig.4. Training and checking data used for ANFIS prediction**

![Membership functions on inputs](image)

**Fig.5. Initial membership functions on inputs**

3. RESULTS

The error curves for both checking and training data are shown in Figure 6. Training error was represented by circles and checking error by squares. It can be noted that training error is higher than checking error, which is common process in non-linear regression. It could indicate that the training process is not close to finished yet. It can be also seen that the training procedure was lasted for 10 epochs. Figure 7 shows the time series prediction of voltage changing obtained using ANFIS. The ANFIS prediction results were represented by dotted line and experimental results by solid line. Here the difference between predicted values and measured values is negligible. Figure 8 shows the prediction error. It is found that the maximal error is 0.06V which does not result any change in the control signal since this conductive silicone rubber cannot be used for accurate measurements because of strong non-linearity. Selection of number of membership functions, training data and epoch are obtained by trial and error. For further improvements, the number of membership functions have to be increased which results in slower training procedure. Fuzzy Logic Toolbox of MATLAB was used to develop the ANFIS model with four inputs and single output as given in Figure 9.
4. CONCLUSION

In this paper a new constitutive model was presented that allows predictions of the voltage changing behaviour of elastomeric materials. The most important advantage of such a model is the ability of real time identification of conductive silicone rubber electrical behavior, which can be used for strain sensing structure or other applications of this material. ANFIS is used to approximate correlation between measured features of the material and to predict its unknown future behaviour for voltage changing. The implementation of ANFIS model is less complicated than that of sophisticated identification and optimization procedures. Compared to fuzzy logic systems, ANFIS has automated identification algorithm and easier design and compared to neural networks it has less number of parameters and faster adaptation. The non-linear characteristics of the conductive silicone rubber can be tolerably handled in the proposed system. This prediction could be utilized as input for the strain sensing control system. Possibility to reduce the number of sensors and connections improve the performance of control strategy. The ANFIS based time series prediction model for voltage changing of conductive silicone rubber is unique and novel as it is simple, reliable and easily accessible for different compression conditions.

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