Intelligent processing of acoustic emission data based on cluster analysis

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Abstract. In this paper, we propose to examine the neural network approach to the problem of calculating the characteristics of the deformation and fracture of metals by transforming the fuzzy clustering of pulses of acoustic emission. To solve the problem of division the metal samples into two classes (deformed and non-deformed) we separated signals from the samples using two algorithms, i.e. fuzzy clustering and neural network. 2 clusters were always formed corresponding to 2 types of signals. The error of the neural network tests was within 5%. Thus, by this approach one can achieve sub-pixel sampling of acoustic data on clusters and neural network learning algorithm for the automatic calculation of the characteristics of metals.

1. Introduction

According to the authors of this paper, one can now single out a whole direction in the theoretical computer science (connected, of course, with the analysis of big data), which can be called a detailed analysis of the data available on the Internet, and, most importantly, obtaining on the basis of these data results that are very useful to the task managers in the subject areas themselves. In this case, the methods of obtaining these results (including feature selection based on the analysis of these data, big data) can be quite different, i.e. from pure rule-based approaches to their complete opposite. Let us note in advance, that we consider our methods of this paper lying between these two opposites.

Apparently, no less interesting than methods, are subject areas to which this approach is applicable. We can briefly mention the following completely different subject areas, in which significant successes have been achieved in recent years thanks to such approaches, i.e. based on data from the Internet: the research of graph models in social networks; solving various astronomical problems; some problems in computer games programming… Certainly, we can also mention some problems of experimental physics, but among very numerous such problems, we mention only the previously unknown phenomenon of the formation of a self-sustaining high-temperature conductive layer (so-called T-layer) under non-stationary motion in a magnetic field of a compressible medium. Besides, it is the subject of this paper is the research results of acoustic emission data.

However, among many papers known to the authors of this article, which are devoted to the mathematical modeling of acoustic emission, we almost do not see the work in which the measurement data
would be investigated using neural networks. We shall mention only the following works related to the subject under consideration: [1, 2, 3].

Thus, this paper is an attempt to apply some of the algorithms we used earlier in various discrete optimization problems [4, 5] in a new field, i.e. for numerical study of results of the acoustic emission. See also the work of one of the authors of this paper [6].

The questions of processing different experimental data using neural networks are widely represented in the literature [7]. For the practical application of different tasks, there are particularly interesting calculation, prediction and recognition. Each type of these tasks requires some experimental data for computer modeling and data processing, they are influenced by many factors, such as the availability and accuracy of data, cost analysis, and user preferences calculated results. Meet all the needs, as a rule, is not possible and is always a certain percentage of the outstanding conditions, so use one of the clustering algorithms with which try to solve our problems.

The general statement of the problem is the following. It is necessary to calculate the time of a malfunction or failure of metals based on acoustic emission. The experimental data are pre-processed using fuzzy clustering. According to the authors, clustering is actually the main task for acoustic emission data investigation and intelligent processing.

2. The method of acoustic emission

The acoustic emission (AE) is the phenomenon of the emergence and propagation of elastic waves (acoustic waves) during the deformation stress of the material. Quantitatively, AE is material integrity criterion, which determines the sound radiation of the material at the test load. The effect of acoustic emission can be used to determine the formation of defects in the initial stage of structural failure. It can also be used to determine the level of seismic hazard geological rocks, with emission levels may cause artificially [8]. Basic diagnostics civil engineering and construction is a passive collection of information from multiple acoustic (or ultrasonic) sensors, and treated for determination of the degree of wear design.

Figures 1 and 2 show some examples of some of the momentum of acoustic emission data are processed for cluster analysis and are input to the neural network.

![Figure 1. Examples of the speakers pulse propagation of acoustic emission.](image1)

![Figure 2. Examples of the speakers pulse propagation of acoustic emission.](image2)

Figure 2 shows that the lower the noise signal is varies within acceptable values and the top has a single jump range.

Figure 3 lists the most troubled areas, but have shown the effects of the test sample (in this case, the spectrum of pure copper). The problem is that, in such cases, with the physical and chemical properties of the metal, using a neural network to calculate the state of the metal at the moment and build a forecast for the future. When registering acoustic emission signal we consider it the amplitude of oscillation depends on the time.
3. The use of fuzzy c-means clustering method

Cluster analysis is a task decomposition of a given sample of objects (cases) into subsets called clusters, such that each cluster consists of similar objects, and objects of different clusters were significantly different. For AE data analysis, we use the fuzzy clustering algorithm, as it is simple to implement and satisfactory for data post-processing.

The most common example is the implementation of the algorithm of cluster analysis algorithm objects forming the shape of the “butterfly”. We can speak, that Figure 1 also shows an example of the implementation of this clustering algorithm. Elements of the “+” are the centers of clusters, in the red circles are the elements belonging to the 1st cluster (circles left monochrome picture), in blue to the 2nd (the circles on the right), the point at the center of the figure refers to the two clusters [9].

The basis of this algorithm is the following procedure. Suppose, we are given $X = (X_1, X_2, \ldots, X_n)^T$, where $X$ is the set of objects to be clustering ($n$ is number of objects). Each object $X_k = (x_{k1}, x_{k2}, \ldots, x_{kp})$ represents a point in p-dimensional feature space $k = 1, n$. $c$ is number of clusters $2 \leq c < n$. Need every element of $X$ associate degree belonging to the cluster.

The members of the same cluster should be as close to each one as possible and, at the same time, the clusters have to be at the greatest distance from each other. To control the process of clustering to use a measure of proximity, which is usually defined as the distance between two objects, which must be greater than 0. Any partition of the set $X = (X_1, X_2, \ldots, X_n)^T$ into fuzzy subsets $S_i (i = 1, c)$ can be completely described by the membership function $\mu_{ik}: X \rightarrow [0, 1]$.

We denote $\mu_{ik}$ degree of membership of the object $X_i = (x_{i1}, x_{i2}, \ldots, x_{ip})$ subset $S_i$, that is $\mu_{ik} = \mu_{ik}(X_i)$. and through $V_c$ is the set of all real matrices of size $c \times n$. Then the fuzzy c-partition (or degree of membership matrix) is the matrix $M = [\mu_{ik}] \in V_c$ under the following conditions:

1) $\mu_{ik} \in [0, 1], i = 1, c, k = 1, n$;

2) $\sum_{i=1}^{c} \mu_{ik} = 1, k = 1, n$;
3) \[ \sum_{k=1}^{n} \mu_{ik} \in (0, n), i = 1, \ldots, c. \]

So, in contrast to the precise, with a fuzzy c-partition of any object at the same time belong to different clusters but with a different degree [10]. Conditions (2) and (3) requires only that the sum of the powers of the object belonging to all clusters was normalized to 1, and that the number of clusters to which the object belongs, not to exceed c. Denote the centers of the clusters, that is, a points in p-dimensional space, which are concentrated around the corresponding objects in \( V_i = (v_{ik}, v_{i2}, \ldots, v_{ip}), i = 1, \ldots, c \). Use the Euclidean distance for the problem of fuzzy clustering, it is to find such a matrix M and the degree of membership of the coordinates of cluster centers \( V = (V_1, \ldots, V_c) \), that provide at least the following criteria:

\[ \sum_{i=1}^{c} \sum_{k=1}^{n} (\mu_{ik})^m \| X_i - V_i \| \rightarrow \min, \]

where \( V_i = \frac{1}{\sum_{k=1}^{n} \mu_{ik}} \sum_{k=1}^{n} (\mu_{ik})^m \cdot X_k \) is the center of the i-th cluster \( i = 1, \ldots, c \); \( m \) is the so-called exponential weight \((m \geq 1)\). The value of the exponential weight is set before clustering. Exponential weight \( m \) matrix affects the grade of membership. The larger \( m \), the final matrix c-partition is more “spread”, and if \( m \rightarrow \infty \) it takes the form \( M = [1/c] \) (see also [10]).

![Figure 4. An example of clustering the spectrum of AE.](image)

This algorithm helps to achieve the decomposition of the spectrum into clusters AE. Thus, we have clustered the data for further processing. Figure 4 shows an example of a partition into clusters of points AE: White ovals outlined points that belong to the 1st cluster (circles to the left of the selected area, monochrome picture), respectively yellow marked points relating to the 2nd cluster (circles to the right of the selected area, monochrome drawing), green marked points that apply to the 1st and to the 2nd cluster (circles are in the selected area).

4. Neural network algorithm for computing signs of deformation and fracture of metals

After splitting the points into clusters, the data we use for further processing algorithm computations. It is based on the following procedure:

1) the algorithm takes the data converted and full spectrum of the transformed clustering AE;
2) we determine the critical points of the spectrum of AE (the so-called critical moments of greatest vibration spectrum AE);
3) we train the network, on the basis of full and transformed view of the spectrum of AE data;
4) after a successful training network, we use the full check of AE (currently, we have another spectrum);
5) in the event of critical moments, the “resulting algorithm” tells about the signs that there are moments of destruction of materials.

The first step we obtain the data of cluster analysis for further processing, as well as the initial spectrum of AE to compare the results.

When you highlight the critical moments we choose coordinates which are removed from the coordinate space X over 100-200 U/mV, the other coordinates are largely noise. After this, data is presented in the neural network. In its turn, it receives the full range of data and clustering of all the transformations highlighted by the critical points. As the neural network, we used a multilayer perceptron. For processing using point coordinates are not in the range of noise. When learning neural network solves the problem of interpolation, for recovery of the objective function over the set of training data sets [11]. A multilayer perceptron trained on the basis of receiving the results of oscillations, whereby we can remember over the spectrum of AE. Inverse algorithm the error to train the neural network allows, so that the error of hidden layers of neurons as a result affect the final output layer neurons [12, 13]. After training, we use for other parts of the spectrum of AE. Next, we use the trained neural network to test the resulting outcomes and experiments with other parts of the spectrum and the other spectra of AE.

![Comparison of the spectrum AE from the oscilloscope and AE obtained from trained neural network](image)

**Figure 5.** Comparison of the spectrum AE from the oscilloscope and AE obtained from trained neural network K.

In the event, the highest frequency notified of the event, marking this critical point. With the above described algorithm can solve the problem of determination of critical moments and the Kaiser effect, tracking changes in the spectrum for automatic analysis.

5. **Conclusion and explanation of results**

Data clustering were conducted by the package MATLAB and our C++ implementation. As a result of the above algorithm turned achieve:

- the decomposition of the spectrum into clusters AE;
• selection of the highest vibration and noise limit;
• preparation of trained neural network to detect in different parts of the spectrum and the highest vibration Kaiser effects;
• automatic notification of the occurrence of the above-mentioned oscillations using the trained neural network.

Through the above described algorithm can get good training results, and 80% of the errors in the output layer are eliminated in the further processing of the data. Thus, we separate the signals using two algorithms, i.e. fuzzy clustering and neural network., 2 clusters were always formed; this was a good result because the signals were of 2 types. The error that the tests gave for the neural network was within 5%. By this approach one can achieve sub-pixel sampling of acoustic data on clusters and neural network learning algorithm for the automatic calculation of the characteristics of metals when exposed to it.

An example of the algorithm is shown in Figure 5.

The upper range of the acoustic emission is taken from the converter and the converted multi-channel digital oscilloscope and is the initial spectrum.

And a lower range of the acoustic emission converted and obtained using a trained neural network. You can see in the picture are slightly different spectra, this error of neural network training. But with such inaccuracies, the result looks very acceptable.

Compared with the algorithm based on wavelet transformation of the data analysis, the algorithm gains in speed performance, but by definition the decision, the results obtained are sometimes worse, see [6] etc. This is directly related to the fuzzy clustering algorithm, that is more clusters c, the better will be the result of the work, but the speed of the algorithm is slower.

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