Lecture Notes in Computational Intelligence and Decision Making

Advances in Intelligent Systems and Computing

Volume 1020

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Lecture Notes in Computational Intelligence and Decision Making

Collecting, analysis, and processing information are one of the current directions of modern computer science. Many areas of current existence generate a wealth of information which should be stored in a structured manner, analyzed, and processed appropriately in order to gain the knowledge concerning investigated process or object. Creating new modern information and computer technologies for data analysis and processing in various fields of data mining and machine learning create the conditions for increasing effectiveness of the information processing by both the decrease of time and the increase of accuracy of the data processing.

The international scientific conference “Intellectual Decision-Making Systems and Problems of Computational Intelligence” is a series of conferences performed in East Europe. They are very important for this geographic region since the topics of the conference cover the modern directions in the field of artificial and computational intelligence, data mining, machine learning, and decision making.

The conference is dedicated to the memory of Professor, Academician of the National Academy of Sciences of Ukraine Yuriy Kryvonos (April 12, 1939–February 12, 2017). Professor Y. Kryvonos was a well-known specialist in informatics, mathematical modeling, and artificial intelligence. Under his leadership, the fundamentals of the perturbation theory of pseudo-inverse and projection operators, the theory of analysis, and synthesis of high-quality clustering systems, recognition, and prediction of information were developed. In his studies, tools were identified for the optimal synthesis of linear and nonlinear recursive data classification systems (pattern recognition) and methods for analyzing and synthesizing voice speech information were proposed. He has developed a unified approach to solving problems of modeling wave and fast physical and technological processes and a new approach to the synthesis of active artificial media with desired properties. The distributed information technologies based on the concept of an electronic document have been created under his leadership too. Yuriy Kryvonos was one of the founders of this conference, the chairman of the program, and international committees.
The aim of the conference is the reflection of the most recent developments in the fields of artificial and computational intelligence used for solving problems in variety areas of scientific researches related to data mining, machine learning, and decision making.

The 15th International ISDMCI Scientific Conference (ISDMCI’2019) held in Zaliznyi Port, Kherson region, Ukraine, from May 21 to 25, 2019, was a continuation of the highly successful ISDMCI conference series started in 2004. For many years, ISDMCI has been attracting hundreds or even thousands of researchers and professionals working in the field of artificial intelligence and decision making. This volume consists of 49 carefully selected papers that are assigned to three thematic sections:

Section 1. **Analysis and Modeling of Complex Systems and Processes:**
- Methods and means of system modeling in the conditions of uncertainty
- Problems of identification of complex system models and processes
- Modeling of operated complex systems
- Modeling of various nature dynamic objects
- Time series forecasting and modeling
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Section 2. **Theoretical and Applied Aspects of Decision-Making Systems:**
- Decision-making methods
- Multicriteria models of decision making in the conditions of uncertainty
- Expert systems of decision making
- Methods of artificial intelligence in decision-making systems
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Section 3. **Computational Intelligence and Inductive Modeling:**
- Inductive methods of model synthesis
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- Multiagent systems
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- Bayesian networks
- Hybrid systems and models
- Fractals and problems of synergetics
- Images’ recognition and cluster analysis
We hope that the broad scope of topics related to the fields of artificial intelligence and decision making covered in this proceedings volume will help the reader to understand that the methods of data mining and machine learning have become an important element of modern computer science.

June 2019

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Volodymyr Stepashko
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Analysis and Modeling of Complex Systems and Processes
Soft Filtering of Acoustic Emission Signals Based on the Complex Use of Huang Transform and Wavelet Analysis

Sergii Babichev¹,²(✉), Oleksandr Shanko³, Artem Shanko⁴, and Oleksandr Mikhaliov⁵

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Abstract. The paper presents the results of the research concerning development of acoustic emission signals soft filtering model based on the complex use of Huang transform and wavelet analysis. The acoustic emission signals which were generated during crack progression from initiation to final failure with several distinct phases have been used as the experimental signals during the simulation process. The families of biorthogonal wavelets were used during the filtering process. The Shannon entropy criterion which was calculated with the use of James-Stein estimator was used as the main criterion to estimate the filtering process quality. The optimal parameters of the wavelet filter (type of wavelet, level of wavelet decomposition, value of the thresholding coefficient) were determined based on the minimum value of the Shannon entropies ratio which were calculated for filtered signal and for allocated noise component.

Keywords: Acoustic emission signal · Filtering · Wavelet analysis · Huang transform · Shannon entropy

1 Introduction

Acoustic emission (AE) technique is one of the current directions of structural state monitoring methods which are developed as an alternative of non-destructive testing methods. Implementation of this technique allows us to perform both the continuous or on-demand diagnostics and discovering defects using permanently installed sensors [1–4]. The main advantages of the AE technique are high level of availability and low maintenance costs. Identification of a defect location is performed by evaluation of the time difference of AE signals arrival to the sensors which are allocated at the different places of the object [5,6]. High
level of noise component which appears at the stages of signal generation, propagation and detection is one of the main reasons which complicates the successful application of this technique. Thus, the filtering of initial AE signal in order to remove the noise component is the one of the necessary conditions of the AE signals processing technique successful implementation.

A lot of techniques for different types of signals filtering exist nowadays. So, in [7–9] the authors presented the signal processing methods based on smoothing the signal by the use of both the extrapolation technique and minimizing the mean square error between the estimated random and the desired processes. The main disadvantage of these techniques is their low effectiveness in the case of processing of non-stationary and non-linear signals with local particularities. Implementation of these techniques in these cases promotes to the loss of the large amount of useful information. The current methods of non-stationary and non-linear signals processing are based on decomposition of the signal with allocation of its components and the following processing of these components in order to remove the noise. The paper [10] presents the results of the research concerning the use of fast Fourier transform for evaluation of the anisotropic relaxation of composites and nonwovens. Implementation of the fast Fourier transforms technique for time-frequency analysis of pressure pulsation signal is presented in [11]. The frequency spectrum including frequency-domain structure and approximate frequency-scope was obtained during the simulation process. However, it should be noted, that fast Fourier transform technique is effective in the case of stationary signals processing. In the case of non-stationary and non-linear signal processing the effectiveness of this technique decreases.

An alternative and logical continuation of the fast Fourier transforms technique is wavelet analysis [12–15]. Implementation of this technique involves wavelet-decomposition on levels from 1 to N with calculation of both the approximation coefficients on N-th level and the detail coefficients on levels from 1 to N. In the most cases the detail coefficients contain the noise component, thus these coefficients should be processed during the filtering process. Reconstruction of the signal is performed with the use of both the approximation coefficients and the processed detail coefficients. The effectiveness of this technique implementation depends on the choice of the type of the used wavelet, level of the wavelet decomposition and the thresholding coefficient value to process of the detail coefficients. It should be noted that effective techniques for these parameters objective determining are absent nowadays. Moreover, the direct implementation of this technique for signals processing increases the requirements to the wavelet filter parameters determination. In this case more effective can be techniques which are based on decomposition of the signal into components with the further allocation and wavelet-processing of the noised components.

In [16,17] the authors proposed the use of the empirical mode decomposition (EMD) method based on complex use of both the Huang transform and Hilbert spectrum for non-stationary and non-linear signals analysis and processing. The main concept of this method consists in decomposition of the initial signal into mutually independent intrinsic mode functions (IMFs) based on
Huang transform. Then, the Hilbert spectrum is formed by applying the Hilbert transform to the obtained modes (IMFs). The analysis of the Hilbert spectrum for the allocated modes allows us to receive the detail information concerning particularities of the investigated signal. Nowadays the Hilbert-Huang technique has been implemented in various fields of scientific research. So, the paper [18] presents the technique to decompose the multicomponent micro–Doppler signals based on the complex use of Hilbert-Huang transform and analytical mode decomposition (HHT-AMD). The approach concerning the implementation of the Hilbert-Huang transform (HHT) for detection, diagnostic and prediction of the degradation in the ball bearing is proposed in [19]. The papers [20–22] present the results of the research concerning implementation of the HHT for analysis of the vibration signals from different objects. In the paper [23] the authors present the results of the research concerning the use of HHT for the processing and analysing of ECG signal in order to diagnose the brain functionality abnormalities. The results of the research concerning the implementation of the HHT for the analysis of the non-stationary financial time series and the acoustic wave frequency spectrum characteristics of rock mass under blasting damage are presented in the papers [24,25]. However, it should be noted that in spite of the achievements in this subject area the problem of denoising of the non-stationary and non-linear signals has no effective solution nowadays. This problem can be solved based on the complex use of modern techniques of both the data mining and machine learning which are applied successfully in different areas of the scientific research nowadays [26–29]. In this paper we propose the technique of acoustic emission signals filtering based on the complex use of both the Huang empirical mode decomposition method and wavelet analysis. The optimal parameters of the wavelet filter for each of the intrinsic modes are determined on the basis of the quantitative criterion minimum value which is calculated as the ratio of Shannon entropies for the filtered data and for the allocated noise component.

**The aim of the research** is the development of technique of acoustic emission signals filtering based on the complex use of Huang transform and wavelet analysis.

### 2 Materials and Methods

The Huang transform technique involves that initial signal is a complex one and it can be decomposed into intrinsic mode functions (IMFs) [16]:

\[
y(x) = \sum_{i=1}^{n} f_i(x) + r_n(x)
\]

where \(n\) is the number of the IMFs functions, \(f_i(x)\) is the IMFs function on \(i\)-th level of the signal decomposition, \(r_n(x)\) is the residual function, which represent the average trend of the investigated signal. Implementation of the Huang empirical mode decomposition technique (EMD) intendes the following conditions:
the number of each of the IMF's functions extrema and the number of zero crossing should be equal or not differ by more than one;
- in any point of the IMF's function the mean value of the envelope defined by local maximums and local minimums should be zero.

The signal decomposition process is stopped if one of the following conditions is performed:
- the residual function $r_n(x)$ does not contain more than 2-3 extrema points;
- the residual function $r_n(x)$ in whole interval of $x$ change is insignificant in comparison with appropriate values of the IMF's functions.

A structural block-chart of the step-by-step process of the signal filtering based on the complex use of Huang empirical mode decomposition technique and wavelet analysis is presented in Fig. 1. As it can be seen, the result of the Huang transform is selection of the IMF's functions which contain the noise component for purpose of their further filtering using discrete wavelet transform. Figure 2 presents the main idea of the discrete wavelet decomposition process. Implementation of this process involves calculation of both the approximation coefficients at $N$-th level and the detail coefficients at levels from 1 to $N$ using the low frequency (LF) and high frequency (HF) filters:

$$y(x) \rightarrow \{CA(N), CD(N), ..., CD(2), CD(1)\}$$

(2)

The noise component in the most cases is contained in detail coefficients therefore these coefficients should be processed during the signal processing. To process the detail coefficients we propose to use the soft thresholding in accordance with the following conditions:

$$
\begin{align*}
    d &= 0, & \text{if } d \leq \tau \\
    d &= d - \tau, & \text{if } d > \tau
\end{align*}
$$

(3)
where $d$ is the detail coefficient and $\tau$ is the thresholding coefficient value. It is obvious, that quality of wavelet filtering process depends on type of the used wavelet, level of the wavelet decomposition and thresholding coefficient value to process the detail coefficients. In [15] the authors proposed the technology to determine the optimal parameters of the wavelet filter based on the use of the Shannon entropy criterion which is calculated on the basis of James-Stein estimator [30]. This method is based on the complex use of two different models: a high-dimensional model with low bias and high variance, and a lower dimensional model with larger bias but smaller variance. Evaluation of the values distribution probability in a cell in accordance with the James-Stein shrinkage method is calculated in the following way:

$$p_{i}^{Shrink} = \lambda p_i + (1 - \lambda)p_{i}^{ML}$$

(4)

where $p_{i}^{ML}$ is the probability of the values distribution in the $i$-th cell, which is calculated by the maximum likelihood method; $p_i = \frac{1}{n_i}$ is the maximum entropy target in the $i$-th cell; $n_i$ is the number of the features in this cell. It is obvious, that $p_{i}^{ML}$ corresponds to the high-dimensional model with low bias and high variance and $p_i$ is the estimation with higher bias and lower variance of the features distribution. Intensity parameter $\lambda$ in the proposed model is calculated as follows:

$$\lambda = \frac{1 - \sum_{i=1}^{k}(p_{i}^{ML})^2}{(n - 1)\sum_{i=1}^{k}(p_{i} - p_{i}^{ML})^2}$$

(5)

where $n$ is the number of the features in the vector. The value of Shannon entropy is calculated with the use of standard formula taking into account the method of the probability estimation:

$$H^{Shrink} = -\sum_{i=1}^{k} p_{i}^{Shrink} \log_2 p_{i}^{Shrink}$$

(6)
In this paper we propose the technique of the wavelet filter optimal parameters determination based on the use of the ratio of Shannon entropies which are calculated for both the filtered signal and the allocated noise component:

$$RH = \frac{H(\text{filtered signal})}{H(\text{noise component})}$$

(7)

It is obvious that the optimal parameters of the wavelet filter corresponds to the minimum value of the Shannon entropy for filtered signal and the maximum value of this criterion for the allocated noise component. In this case the value of the relative criterion (7) should be achieved the minimum one. The structural block chart of the process of this criterion calculation within the framework of the proposed technique is presented in Fig. 3. Figure 4 shows the structural block chart of the algorithm to determine the wavelet filter optimal parameters. The stages of this algorithm implementation are the following:

Stage I. Signal loading and Huang transform performing.
2. Visualization and analysis of the obtained modes. Allocation of the noised modes for their following processing.

Stage II. Wavelet filtering of the selected modes.
3. Setup the ranges and the steps of the wavelet filter parameters change.
   3.1 Formation of the vector of different types of wavelets for the appropriate mother wavelet.
   3.2 Calculation of the thresholding coefficients initial value to process the detail coefficients:

$$\tau_0 = \sigma \sqrt{2 \ln k}$$

where \( k \) is the length of the investigated signal; \( \sigma \) is the median absolute deviation for the allocated detail coefficients:

$$\sigma = \delta \cdot (|CD(i) - \text{median}(CD(i))|)$$

where \( i = 1, ..., n \) is the wavelet decomposition level, coefficient \( \delta \) is determined empirically during the simulation process.
Fig. 4. A structural block chart of the algorithm to determine the wavelet filter optimal parameters
3.3 Formation of the range and the step of the thresholding parameter value change:

\[ \tau_{\min} = 0.1\tau; \quad \tau_{\max} = 5\tau \quad d\tau = 0.02 \cdot (\tau_{\max} - \tau_{\min}) \]

3.4 Evaluation of the wavelet decomposition maximum level.

4. Determination of the optimal type of the wavelet.
   4.1 Initialization of the counter, which corresponds to the first wavelet in the appropriate sequence \((j = 1)\). Setup of the initial values of both the wavelet decomposition level \((N = 3)\) and the thresholding coefficient value \((\tau = \tau_0)\).
   4.2 Discrete wavelet decomposition of the signal with calculation of both the approximation coefficients at the \(N\)-th decomposition level and the detail coefficients at the levels from 1 to \(N\).
   4.3 Soft thresholding of the detail coefficients using the conditions (3).
   4.4 Reconstruction of the signal based on both the approximation coefficients and the processed detail coefficients.

5. Calculation of the data processing quality criteria.
   5.1 Extraction of the noise component as the difference of both the initial and filtered signals.
   5.2 Calculation of the Shannon entropies for the filtered signal and for the allocated noise component by the formula (6). Calculation of their ratio by the formula (7).
   5.3 If the counter value is maximal, the results analysis and fixation of the optimal type of wavelet which corresponds to the minimum value of the criterion (7). Otherwise, increment of the counter value and go to the step 4.2 of this procedure.

6. Determination of the optimal wavelet decomposition level.
   6.1 Initialization of the counter, which corresponds to the first level of wavelet decomposition \((z = 1)\).
   6.2 Repetition of the steps from 4.2 to 5.3 of this procedure.
   6.3 If the counter value is maximal, the results analysis and fixation of the optimal wavelet decomposition level. Otherwise, increment of the counter value and go to the step 6.2 of this procedure.

7. Determination of the thresholding coefficient optimal value.
   7.1 Initialization of the counter \((v = 1)\), which corresponds to the minimum value of the thresholding coefficient: \((\tau = \tau_{\min})\).
   7.2 Repetition of the steps from 4.2 to 5.3 of this procedure.
   7.3 If the counter value is maximal, the results analysis and fixation of the thresholding coefficient optimal value. Otherwise, increment of the counter value and go to the step 7.2 of this procedure.

8. Filtering of the current IMFs function with the use of the wavelet filter optimal parameters.

9. Repetition of the stage 2 for other of the allocated IMFs functions.

Stage III. Reconstruction of the signal.

10. Reconstruction of the signal with the use of both the processed and non-processed components of the signal.
3 Experiment

The experimental device which were used to fixation of the acoustic emission signals for the different levels of mechanical loading of the tested material is shown in Fig. 5. The experimental device contains three main mechanisms: the deformation, the force-fixation and the AE signal fixation mechanisms. The samples for four-point bend test were cutted out from steel flat in the size $300 \times 20 \times 4$ mm. The simulation process involved the fixation of both the AE signals and the level of the sample deformation for different levels of the tested sample loading. The broadband sensors for acoustic emission instrument AF15 with a bandwidthes of 0.2–2.0 was used as the measurement device. The artificial load was step-by-step increased from 150 N to 400 N with fixation of the AE signals for different values of the sample deformation. The examples of the AE signals which were obtained during the simulation process are shown in Fig. 6. As it can be seen, the shape of the signals is changed during the load increase. However, the existence the noise component complicates the obtained results interpretation. Thus, at the first step it is necessary to decrease the level of the noise component with saving useful information concerning state of the investigated sample. The familiy of biorthogonal wavelets were used during the simulation process within the framework of the hereinbefore technique.

![Image](image_url)

Fig. 5. Four-point bend test device: (1) test sample; (2) support; (3) deformation indicator; (4) AE signal indicator

4 Results and Discussion

Figure 7 presents the result of the Huang empirical modes decomposition implementation for the signal which is shown in Fig. 6g. The same results were obtained for other signals. The analysis of the IMF's functions allows us to conclude that the first and the second modes contain the noise component, thus these modes should be processed for the signal denoise. Figure 8 presents the results of the simulation
Fig. 6. AE signals for different levels of the sample deformation concerning determination of the optimal wavelet from the family of the biorthogonal ones in terms of the minimum value of the criterion (7). The results of the simulation has shown that the biorthogonal wavelet $\text{bior}1.1$ is the optimal one for processing both the IMFs 1 and IMFs 2 functions since the criterion values of Shannon entropies ratio which have been calculated by the formula (7) achieved the minima values in these cases. Figure 9 shows the results of the simulation concerning determination of the optimal wavelet decomposition level in the cases of the use of both the IMFs 1 and IMFs 2 functions. The analysis of the obtained charts allows us to conclude that the wavelet decomposition levels 7 and 8 are the optimal in terms of the criterion (7) minima for the functions IMFs 1 and IMFs 2 respectively. Figure 10 presents the same results in the case of the thresholding coefficient optimal values determination. The range and the step of the thresholding coefficient value change was determined in accordance with the steps 3.2 and 3.3 of the hereinbefore described algorithm. The value of multiplier $\delta$ was taken as 0.5. The optimal value of the thresholding coefficient was determined as the first achieved of