A Damage Identification Method for Messenger Wire in Electrified Railway Based on Improved Synergetics

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Abstract: - Facing the problem of damage identification of messenger wire in the complex environment, a damage identification method for messenger wire in electrified railway based on improved Synergetics is put forward. Firstly, the method establishes a preliminary recognition mechanism, which includes the kinetic process of damage recognition, the development of cooperative identification model and the features extraction for messenger wire. Subsequently, this paper introduces the feedback identification mechanism combined by features evaluation and eigenvector reconstruction processes, which can be used to rise the correct rate of recognition. The experiment results showed that in the disturbance and noisy rich environments, the proposed method can identify different depths of cracks well, and the correct rate of recognition has risen to 100% when the feedback identification mechanism is introduced. This proposed approach not only demonstrates a strong ability to reject noise and disturbance, but also overcomes some shortcomings, such as the requirement of massive samples, being vulnerable to environments. Therefore, it will lay the foundation for the structure damage identification in the other more complex environments.

Key-Words: - Synergetics; Messenger wire; Damage Identification; Feedback Mechanism

1 Introduction

As the main load-bearing parts of pantograph catenary system for electrified railway, messenger wire can be damaged easily by frequent occurrences of natural disasters and increased serviceability time, which takes a heavy toll on people's lives and properties. According to the service condition and structural characteristics of messenger wire, influences and treatment schemes are different for various damages. Therefore, it is necessary for detection systems to quickly and effectively identify different types of damages, and studying the damage identification method for messenger wire is becoming an urgent problem in structural health monitoring area. However, facing the damage identification of long-distance messenger wire in noisy and disturbance rich environment, the detection signals can easily be disturbed, which has been an enormous challenge for existing identification methods.

In recent years, various artificial intelligence and pattern recognition technologies have been applied to damage detection and identification of messenger wire with strands. For example, Jacques *et al* [1] researched the principles of damage detection with acoustic emission method and conducted an experiment for obtaining a set of data in time domain. LEE Y J *et al* [2] measured the magnetic field of surface to detect and identify the damage. In addition, Zhou *et al* [3] applied eddy current testing method and established a BP neural network for damage recognition of messenger wire with metal strands, using the received signals and number of broken wire to be the input and output of BP network respectively. Zhao [4] studied the preprocessing and feature extraction of signals with wavelet analysis method, and developed the identification RBF-based model for structural conditions. From the above literature review, it can be found that most of existing methods adopt traditional neural networks to identify the types of damage, although the correct rate of recognition have been some improvement, the demand for samples is still great and results are regularly affected by complex external environment. On the other side, active acoustic emission method has been relatively less applied in the field of messenger wire damage monitoring.

The theory of Synergetics studies individuals in systems how to collaborate with each other to achieve the formation of spatial, time and functional structure. And the decision-making technique based on this theory is effective in dealing with uncertainties of complex systems with a relatively small number of training samples, simple feature extraction process, good performance of anti-disturbance and noise resistance. Synergetics has attracted widespread attention in the world and been widely used in pattern recognition field, such as face, character, traffic state recognition, among others [5].

In the previous research, the authors introduced Synergetics innovatively into pipe structural healthy monitoring and proposed a dynamic cooperative identification method, the performance of the approach was verified [6]. However, Synergetics has never been applied in the field of messenger wire damage identification. The pipe and messenger wire have different structures, leading to the differences of signal propagations and theoretical applications. Therefore, this paper proposed a damage cooperative identification method for messenger wire based on improved Synergetics.

2 Theory of damage identification method for messenger wire

2.1 The frame of new method

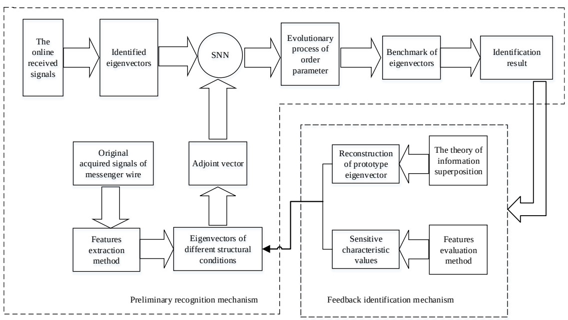

Figure.1 The new damage identification method for messenger wire based on improved Synergetics

An important point of the Synergetics theory is: The process of pattern recognition is the process of pattern formation [7]. Accordingly, a damage cooperative identification approach for messenger wire in electrified railway is developed as shown in figure 1. It is mainly divided into two parts: the preliminary recognition mechanism and the feedback identification mechanism. The first part studies the evolution process of nonlinear kinetics system to realize the damage identification and association functions for messenger wire, and then a cooperative identification model is established and the features extraction in temporal, spectral and transform domains is studied, which makes preliminary classification of damage type. In the second part, the corresponding sensitive features are selected according to evaluation process, and the prototype eigenvectors are reconstructed with the approach based on the theory of information superposition. The feedback mechanism is used to rise the correct rate of recognition.

2.2 The preliminary recognition mechanism of damage for messenger wire

2.2.1 The kinetic process of damage recognition

Assuming that structural vector q consists of different messenger wire structural conditions, it can be expressed as equation (1):

$$q = (V_1, V_2 ..., V_M) \tag{1}$$

Each eigenvector V represents one structural condition, which can be computed from the acquired signal in the experiment. M represents the number of structural conditions. The eigenvector is made up of all the characteristic values and N components as follows:

$$V = (v_1, v_2 ..., v_N) \tag{2}$$

In generally, conditions of $M \le N$ is guaranteed to satisfy the linearly independence of damage modes.

The identification kinetic equation can be described as follows based on the dynamic method of synergetic cognition [8].

$$\dot{q} = \sum_{k=1}^{M} \lambda_k (v_k^+ q) v_k - B \sum_{k \neq k'} (v_{k'}^+ q)^2 (v_k^+ q) v_k \tag{3}$$
$$-Cq(q^+ q) + F(t)$$

Where $q(0)$ represents the initial value of q, λ_k is called the attention parameter, which only is positive can the recognition process be described. B and C are constant coefficients and $F(t)$ is fluctuating force. The first term $v_k \cdot v_k^+$ is regarded as the learning matrix, q increases exponentially when λ_k is positive, but the third term can restrict growth. And the second can identify information. v_k is constrained by the normalization and zero-mean conditions, it can be described as:

$$\sum_{l=1}^{N} v_{kl} = 0$$
$$\|v_k\|_2 = \left\{ \sum_{l=1}^{N} v_{kl}^2 \right\}^{1/2} = 1 \tag{4}$$

To minimize dimension, the order parameter ξ_k is introduced in this method. And then the structural vector q can be expressed as equation (5):

$$q = \sum_{k=1}^{M} \xi_k v_k + w \tag{5}$$

Based on the orthogonality relation, ξ_k can be described as equation (5), and it represents the projection on v_k in orthogonal least square condition.

$$\xi_k = (v_k^+ q) \tag{6}$$

The states before and after evolution can be obtained as follows:

$$\dot{\xi}_k = \lambda_k \xi_k - B \sum_{k' \neq k} \xi_{k'}^2 \xi_k^2 - C \left(\sum_{k'=1}^{M} \xi_{k'}^2 \right) \xi_k \tag{7}$$

The evolution equation is in consistent with human cognitive process. Then, according to the kinetic equation of evolutionary process for order parameter, the corresponding expression (8) can be acquired on the base of equation (7), where γ represents the iteration step.

$$\xi_k(n+1) - \xi_k(n) = \gamma(\lambda_k - D + B\xi_k^2(n))\xi_k(n),$$

$$D = (B+C) \sum_{k'}^{m} \xi_{k'}^2(n) \tag{8}$$

2.2.2 Establishment of damage cooperative identification model

Therefore, based on the kinetic process of damage recognition above, a Synergetics Neural Network (SNN) based damage cooperative identification model for messenger wire is established in this paper. As shown in figure 2, the model has three layers.

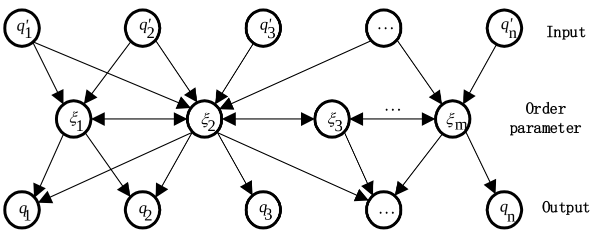

Figure.2 SNN-based cooperative identification model for messenger wire

In the first layer, each internal factor is used to accept inputs of eigenvectors calculated from online received signals of messenger wire, and then the results with synergistic effects are mapped to the second layer. Subsequently, order parameters compete with each other until a certain one wins. Once the recognition network converges to a stable state, external elements in the third layer will output the result, and the winning order parameter corresponds to a certain kind of identified structural condition [9].

2.2.3 Features Extraction for messenger wire

In the damage cooperative identification model, the inputs are the eigenvectors of messenger wire. Therefore, this paper studies the features extraction process, which extracts and segments the information of defects from received signals in temporal, spectral and transform domains to construct eigenvectors. The extracted characteristic values are shown below:

(1) The characteristics of received signal can be reflected directly in temporal domain, therefore, the peak value and crest coefficient are calculated as the first and second features separately, and they are expressed by v_1, v_2.

(2) Root mean square and variance in temporal domain can be used as the third and fourth of features (v_3, v_4).

(3) According to the spectrum analysis of the received data, this paper selects the peak value of spectrum curve and its crest coefficient in spectral domain as the fifth and sixth features (v_5, v_6).

(4) Based on wavelet packet decomposition, the acquired signal is decomposed by db8 wavelet packet with two analysis levels (four coefficients) to calculate the energy and mean square deviation of wavelet coefficients in each frequency band, which are used as eight features and expressed by v_7 to v_{14} respectively.

(5) Then the detected signal is decomposed into a sum of finite intrinsic mode functions(IMF)by empirical mode decomposition(EMD), the energy of the main IMF components is analyzed to be used as the ninth kind of feature(v_{15}).

The above extraction process is applied to calculate features and structure a vector, which can be called eigenvector and described as:

$$V_i = (v_1, v_2, ..., v_{15}) \tag{9}$$

Where V_i can be input into the identification model, the eigenvectors of online measuring data are treated as identified samples. From what we have discussed above, the identification model can make preliminary classification of damage type.

2.3 The feedback identification mechanism

Error recognition often occurs in the process of damage identification. In this section, aiming at rising the correct rate of recognition, a feedback identification mechanism with feature evaluation and eigenvector reconstruction processes is introduced. The sensitive characteristic values can be selected from a large number of features according to the evaluation factors. Then the application of reconstruction algorithm in selecting prototype eigenvector is studied in detail, and criterion of selecting the feedback occasion is designed.

2.3.1 Evaluation process of features extracted from the received signal

In feature space, diverse structural conditions of messenger wire with strands are classified into different classes with its features, and those features in different structural conditions correspond to various regions. For application, features with ideal separability are selected to identify the different damages precisely.

Accordingly, the smaller overlapping part area of regions is, the better the performance of damage types separability will be. Therefore, in the same structural condition, the characteristic distance of features extracted from received signals is small. In contrast, the distance in different structural conditions is long. The features, accord with the above principle, can be considered as the sensitive characteristic values [10].

Assuming that the number of signal samples acquired in different structural conditions is expressed as S, the number of features extracted from each signal sample is N. In the same structural conditions, the average value of features can be described as follows:

$$P_{m,n} = \frac{1}{S}\sum_{u=1}^{S} T_{m,n}(u) \tag{10}$$

Where $T_{m,n}(u)$ represents the m^{th} feature extracted from the u^{th} signal sample in the nth structural condition.

Subsequently, the average distance $P_{m,\mathrm{n}}$ of in different structural conditions can be expressed as equation (11):

$$d_m = \frac{1}{M(M-1)}\sum_{x,y=1}^{M}\left|P_{m,x} - P_{n,y}\right| \tag{11}$$

where $P_{m,x}$ and $P_{m,y}$ represents different average value of features. And then, the difference of one feature from different samples as follows:

$$K = \sum_{\substack{u,v=1\\u\neq v}}^{S}\left|T_{m,n}(u) - T_{m,n}(v)\right| \tag{12}$$

The distance can be expressed as:

$$d_{m,n} = \frac{1}{\mathrm{S(S-1)}}K \tag{13}$$

According to equation (13), the average distance of $d_{m,n}$ can be obtained

$$d'_m = \frac{1}{M}\sum_{m=1}^{M} d_{m,n} \tag{14}$$

Finally, the evaluation factors F_m can be calculated as follows:

$$F_m = \frac{d_m}{d'_m} \tag{15}$$

The bigger F_m is, the more sensitive is the corresponding feature. Based on the theory what we have discussed above, the evaluation method of features is used to select sensitive ones to correctly and rapidly identify the damage of messenger wire.

2.3.2 Reconstruction process of prototype eigenvector

The correct rate of recognition can be raised with the evaluation method, besides, selection of prototype eigenvector is very important to damage recognition of the proposed improved Synergetics approach, which determines the identification performance of this method. Therefore, reconstruction of the eigenvectors helps to improve the recognition results.

In the improved Synergetics approach, the prototype eigenvector has the ability of superposition of information [11], therefore, this paper studies the reconstruction process of eigenvector V. As what we have discussed in section 2.2, each eigenvector V represents one structural condition, assuming that the identified structural vector q extracted from the online received signal of messenger wire is inputted into the identification model, originally the structural vector belongs to V_i which represents structural condition i, but the result demonstrates it corresponds to V_j, then the prototype eigenvector V_i can be reconstructed as follows[12]:

$$V_i' = V_i \times (1-r) + q \times r, \quad r \in (0,1) \tag{16}$$

Where r represents the free parameter determines the level of reconstruction and expresses the difference between prototype eigenvector and identified vector. It is found that good result of experiment can be achieved when $r = 0.7685$ according to comparing the various experimental data. But the value is only effective in this article, as soon as the experimental conditions change, r should be reconfirmed. The input eigenvector will be replaced by V_i' for training if the error identification happens, and the result of samples which are identified incorrectly could be updated.

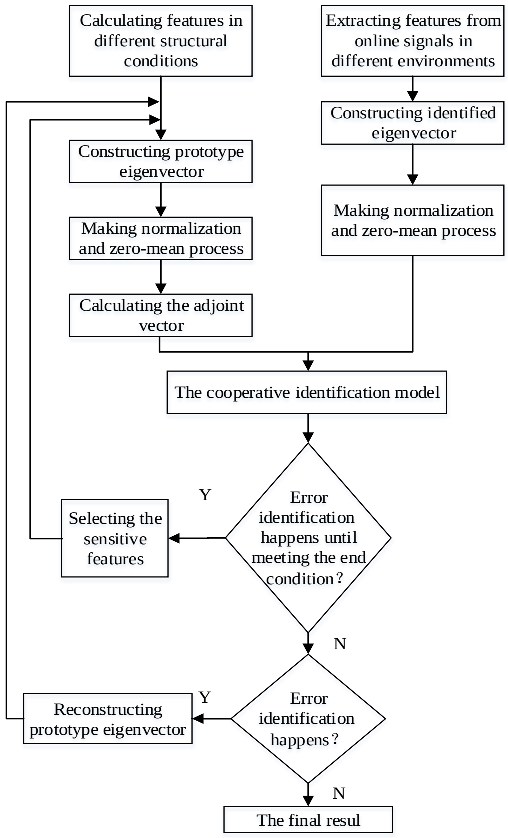

Figure.3 Steps of damage identification method for messenger wire in electrified railway

Above all, the concrete steps of this damage cooperative identification method for messenger wire are as shown in Fig3. Firstly, acquiring signals in different structural conditions, and the corresponding eigenvectors can be used to calculate adjoint vectors. Then the online signals in different environment can be received to construct identified eigenvectors, which are inputted into the cooperative identification model after normalization and zero-mean process. Subsequently, the identification results can be outputted. If the error identification happens, the features evaluation and vectors reconstruction processes will be used to update the results.

3 Experimental validation

An experimental platform for the damage identification of messenger wire was set up to validate the proposed new method. This experiment acquired received signals with active acoustic emission method and then identify different depths of axial cracks of messenger wire structure.

3.1 Experimental platform

In the experimental validation section, the platform was shown in figure 4, which includes computer, data acquisition card, signal generator and amplifier. A messenger wire structure in electrified railway consisted of 19 high tensile steel wires was used as an example, each of wires is 2.5mm in diameter.

The size of piezoceramic transducers (PZT) used in the experiment is 8mm×5mm×1mm. As shown in Figure 5, the bottom of each PZT patch was bonded onto the surface of wires, emitting array and receiving array consisted of four PZT patches separately, and the distance between detection arrays was 12cm. A vibrating motor was connected to messenger wire on the right side of the receiving array. The vibration levels can be adjusted to simulate disturbance rich environment by changing applied voltage and shifting connection position.

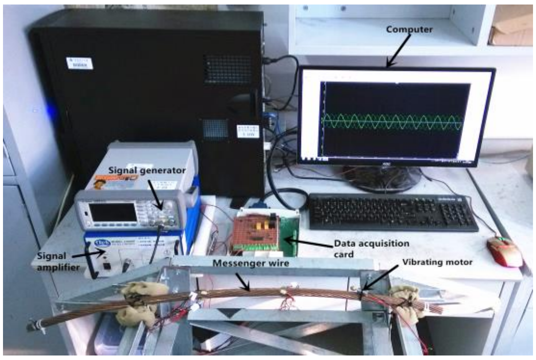

Figure.4 Experimental platform

Figure.5 Detection array layout

3.2 Experimental process and results analysis

In this experiment, a 5 peaks sinusoidal modulation signal used as the dynamic excitation was applied by the signal generator and magnified 50 times by the amplifier. The amplitude was 2.167V and the center frequency of modulation signal was 180 KHz, as shown in figure 6. Upon excitation, emitting array can generate elastic waves and the received result was shown in figure 7. It can be found that the signal of receiving units in experiment provided complex information on structural conditions of the strands in messenger wire.

An axial crack perpendicular to messenger wire was made on the right of the emitting array. The crack size was fixed at 2mm width, but the depth was a variable with 0mm, 1mm, 2mm, 3mm respectively, which represented four structural conditions including the healthy condition, fault1, fault2 and fault3. For different conditions, four signals with structural information could be received after excitation, then eigenvectors extracted from those signals were used to be original training samples.

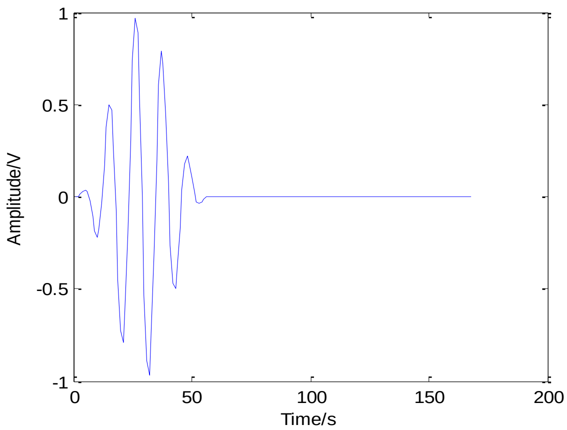

Figure.6 Five peaks sinusoidal modulation signal

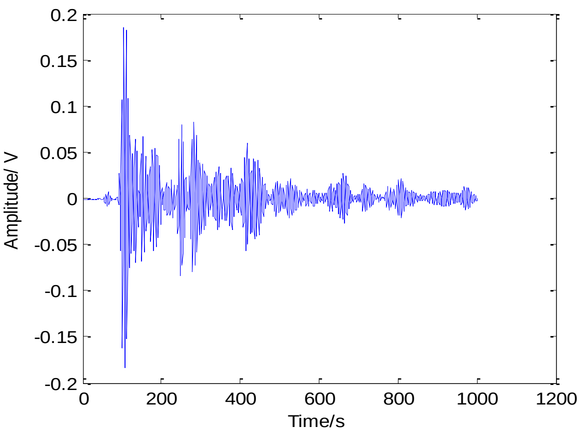

Figure.7 The signal of receiving units in experiment

3.2.1 Experiment in a disturbance environment

On condition that the depth remained constant, shifting the vibrating motor at the distance of 5cm and 10cm from receiving array, applied voltage was changed three times at each position to obtain six vibration levels, then acquiring six records treated as identified signals in different vibration levels. Therefore, a total of 24 measurement signals were obtained for the four structural conditions, and the theory of the extraction method mentioned in section 2.2 was applied to calculate fifteen characteristic values and structure eigenvector V for each identified signal, then the total vectors were input into the identification model as identified samples. The result of preliminary identification is 75%.

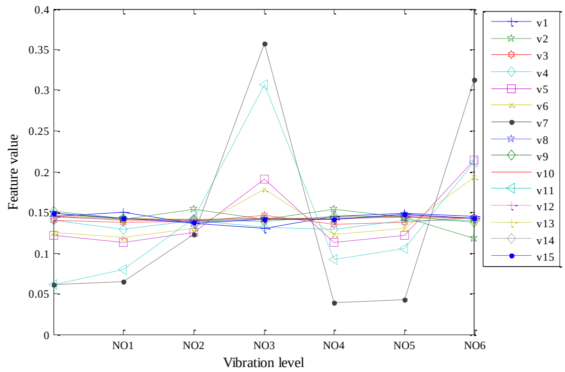

Figure.8 Trend of signal feature values of fault2 in the disturbance environment
(The feature value has been normalized)

Aiming at rising the correct rate of recognition, the feedback identification mechanism was introduced to optimize the result. Firstly, the characteristic values were assessed according to the evaluation method in section 2.3.1, the structural conditions of messenger wire were expressed as $M=4$, the number of signals received is 28, and the features extracted from signals were represented as $N=15$. After evaluation, the sensitive factors F_m calculated from energy (v_7) and mean square deviation (v_{11}) of wavelet coefficient in first frequency band were 0.677692 and 0.87932 respectively, which were relatively small compared to other characteristic values. For example, the factor of mean square deviation of wavelet coefficient in fourth frequency band (v_{14}) is 10.5818. Therefore, those two values were insensitive to damage classification and should not be involved in reconstructing the input eigenvector.

Meanwhile, the trend of characteristic values in the disturbance environment were investigated as shown in Fig 8, taking the values of fault 2 for instance, it could be found that the two values had changed markedly in different vibration levels, which matched the result of evaluation. The reason is the wavelet packets provided a finer decomposition for given signals and gave a better localization, the energy of disturbance distributed in low frequency area, which caused the obvious fluctuation of the two characteristic values. Above all, the selected sensitive features was used to newly identify the damage of messenger wire, and the recognition rate after evaluation process was raised to 83.33%.

Table1 Different identification results in the disturbance environment

Identification period		The depths of crack	The winning order parameter at different vibration levels						Recognition rate
			NO1	NO2	NO3	NO4	NO5	NO6	
Preliminary recognition mechanism		0mm	1	1	1	1	1	1	75%
		1mm	2	2	3	2	2	4	
		2mm	3	3	4	3	3	4	
		3mm	4	4	4	4	3	3	
Feedback Identification mechanism	Evaluation process	0mm	1	1	1	1	1	1	83.33%
		1mm	2	2	3	2	2	4	
		2mm	3	3	4	3	3	3	
		3mm	4	4	4	4	4	3	
	Reconstruction process	0mm	1	1	1	1	1	1	100%
		1mm	2	2	2	2	2	2	
		2mm	3	3	3	3	3	3	
		3mm	4	4	4	4	4	4	

The four depths of crack correspond to different order parameter, $\xi = 1$ represents 0mm, $\xi = 2$ represents 1mm, $\xi = 3$ represents 2mm, $\xi = 4$ represents 3mm.

Then the method based on the theory of information superposition mentioned in section 2.3.2 was applied to restructure prototype eigenvectors consisted of sensitive features, the correct rate of recognition after this process had risen to 100%. The different identification results in the disturbance environment were shown in Table 1, the results demonstrates that the proposed method has a strong ability to reject disturbances, and the result can be optimized when the feedback identification mechanism is introduced.

3.2.2 Experiment in a noisy environment

The depth remained similarly constant, then white Gaussian noise was added to the original four signals in order to simulate external environment. The signal-noise ratio (SNR) is 65, 60, 55, 50, 45, 40, respectively.

Subsequently, 24 signals with noise could be received at different levels. Similarly, the features were extracted to structure eigenvectors and then the vectors were input into the identification model as identified samples. The result of preliminary identification is 87.5%. The features were assessed and the trend was shown in Fig 9. It could be found that the energy (v_9) and mean square deviation (v_{13}) of wavelet coefficient in third frequency band had changed markedly and become insensitive to damage classification. The key reason is the energy of noise distributed in high frequency area when the noisy signals were decomposed by db8 wavelet packet. Therefore, the two insensitive values should be deleted to restructure eigenvectors for training. After evaluation process, the recognition rate was raised to 91.67%.

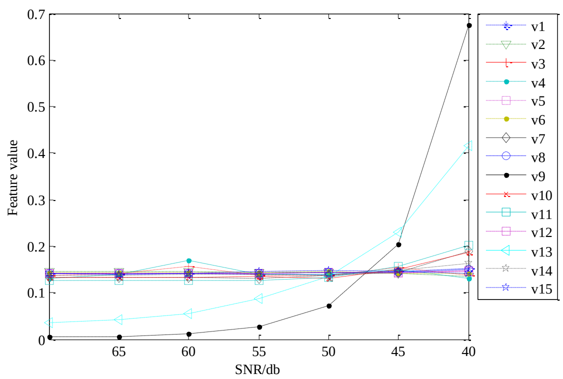

Figure.9 Trend of signal feature values of fault2 in the noisy environment
(The feature value has been normalized)

Table2 Different identification results in the noisy environment

Identification period		The depths of crack	The winning order parameter at different SNR levels (db)						Recognition rate
			65	60	55	50	45	40	
Preliminary recognition mechanism		0mm	1	1	1	1	1	1	87.5%
		1mm	2	2	4	2	2	3	
		2mm	3	3	4	3	3	3	
		3mm	4	4	4	4	4	4	
Feedback Identification mechanism	Evaluation process	0mm	1	1	1	1	1	1	91.67%
		1mm	2	2	4	2	2	2	
		2mm	3	3	4	3	3	3	
		3mm	4	4	4	4	4	4	
	Reconstruction process	0mm	1	1	1	1	1	1	100%
		1mm	2	2	2	2	2	2	
		2mm	3	3	3	3	3	3	
		3mm	4	4	4	4	4	4	

The four depths of crack correspond to different order parameter, $\xi = 1$ represents 0mm, $\xi = 2$ represents 1mm, $\xi = 3$ represents 2mm, $\xi = 4$ represents 3mm.

Then the prototype eigenvectors were reconstructed for re-identification, the result is shown in Table 2, it could be found that the correct rate of recognition had risen to 100%, and the steps of converging to stable state decreased as SNR grown. From what we have discussed above, the proposed approach in this paper can identify correctly different depths of cracks in noisy rich environment.

4 Conclusions

In this paper, a damage cooperative identification method for messenger wire in electrified railway based on improved Synergetics is put forward. The preliminary recognition mechanism innovatively studies the application of Synergetics in messenger wire structure. And the extraction process can collect the damage information comprehensively. As the second part of the proposed approach, the feedback identification mechanism realizes the increase of recognition rate. The evaluation method selects sensitive features to correctly and rapidly identify the damage of messenger wire. And the reconstruction process has the advantage of prototype eigenvector optimization by using the ability of information superposition.

The experiment results showed that in disturbance and noisy rich environments, the proposed new method can identify different depths of cracks well, and the correct rate of recognition has risen to 100% when the feedback identification mechanism is introduced. In summary, the proposed approach is more available than classical recognition method.

Future research will study and improve the feedback identification mechanism, and will also include the identification of other damage types, including wear, strand breakage, and so on.

Acknowledgments

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References:

[1] R C Jacques, J V Flores, T R Strohaecker, Acoustic emission testing in wires from the tensile armour of flexible resers under load, *INSIGHT*, Vol.51, No.9, 2009, pp. 504-507.

[2] LEE Y J, A M N, LEE K S, A development of the fault detection system of wire rope using magnetic flux leakage inspection method and noise filter, *Transactions of the Korean Institute of Electrical Engineers*, Vol.63, No.3, 2014, pp. 418-424.

[3] Zhou Jihui, Liu Dan, He Yuehai, Cao Qingsong, Eddy current nondestructive and quantitative

detection of wire rope based on back propagation neural network, *Machine Tool & Hydraulics*, Vol.40, No.1, 2012, pp. 34-38.

[4] Zhao zhifeng, Research and development of broken wire rope inspection system based on virtual instrument, *Xi'an University of Technology*, 2010.

[5] D Cerra, R Muller, P Reinartz, A classification algorithm for hyperspectral images based on Synergetics theory, *Geoscience and Remote Sensing*, Vol.51, No.5, 2013, pp. 2887-2898.

[6] X B Hong, H Wang, G X Liu, et al, Dynamic cooperative identification based on Synergetics for pipe structural health monitoring with piezoceramic transducers, *Smart Materials and Structures*, Vol.22, No.4, 2013, pp. 3-12.

[7] H.Haken, *Synergetic: Introduction and advanced topics*, Springer, 2004.

[8] H.Haken, *Synergetic computer and cognition*, Springer, 1991.

[9] X B Hong, G X Liu, T Q Chen, Multi-sensor cooperative measurement mechanism based on Synergetics, *The International Society for Optical Engineering*, Vol.7130, 2008, pp. 27-29.

[10] Lei Yaguo, He Zhengjia, Zi Yanyang, Hu Qiao, Mechanical fault diagnosis model based on feature evaluation and neural networks, *Journal of Xi'an Jiaotong University*, Vol.40, No.5, 2006, pp. 558-562.

[11] Wang Hailong, Qi Feihu, Learning algorithm based on the superposition of information, *Journal of infrared and millmeter waves,* Vol.19, No.3, 2000, pp. 205-208.

[12] Wang Weizhi, Liu Binghan, Zhu Minchen, Traffic state recognition based on synergetic method, *Chinese Journal of Stereology and Image Analysis.*Vol.12, No.1, 2007, pp. 38-39.