A Study to Diagnose Subway Gearbox Faults using EMD and OHF Elman ANN

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***Abstract* — In this paper we study the problem of subway gearbox fault that emits a nonlinear and non-stable vibration signal which is difficult to diagnose. We propose a new theoretical method to diagnose this vibration signal. Our method is based on EMD (Empirical Mode Decomposition) and OHF Elman Artificial Neural Network. First, the EMD is used to decompose the original complex signal to obtain Intrinsic Mode Functions (IMF). Then, we construct the feature vectors based on the IMFs. Finally, these feature vectors are input into the OHF Elman neural network as the fault signal samples to train and identify. The experimental results show that the method can identify the faulty gears signal effectively and accurately.**

Keywords-Subway Gearbox; EMD; OHF Elman neural network; fault diagnosis.

I. INTRODUCTION

Urban rail transportation is an important part of large and medium-sized city public transportation system, it plays an important role to alleviate traffic congestion and reduce environmental pollution in city. With the rapid development of China economy, city urbanization gradually accelerated, Chinese dreams mostly perform the subway dreams. Gear and gearbox are the most important parts or equipment of urban rail transit, so the research to fault diagnosis of gear box for subway, which is helpful to reduce equipment repair costs, prevent the occurrence of sudden accident, has great significance to improve the city track traffic safety [1].

The key technology of fault diagnosis is analysis the vibration signal that generated by the equipment. The traditional analysis method of non-stationary signal is map the signal to the frequency domain through the Fourier Transformation, the spectral properties is good, but no temporal information. Through the time-frequency window to solve the localization signal analysis, the Wavelet analysis can analysis the non-stationary signal, but it is still based on Fourier Transformation, can't break the limitation of Fourier Transform [2-3]. Gearbox fault diagnose based on Hilbert demodulation and cestrum is suitable for small interference noise signal. Wavelet packet transform and Hilbert little Potter demodulation spectrum method is based on Wavelet analysis, it's difficult to select basic functions. BP neural network algorithm has problems as extreme value easily happen, the hidden nodes number is difficult to determine and the slow convergence rate [4].

This paper presents a method of fault diagnosis of subway gearbox based on EMD and OHF Elman neural network. EMD has good adaptability for decomposition and noise reduction capability for nonlinear, non-stationary signal [5]. OHF Elman neural network not only has advantages of Elman which has faster convergence speed, less training iterations and more robust to non-stationary signal compared with the BP neural network [6], but also has faster iteration speed, higher sensitivity, and better stability than Elman neural network[7]. The structure of the article is firstly explain and illustrate the EMD and OHF Elman neural network theory, then request the data of gearbox vibration signal after test on subway gearbox test bench, finally obtain experimental results through the method introduced in this paper.

II. THEORY OF EMD AND OHF ELMAN NEURAL NETWORK

A. EMD Model

The principle of EMD method is decompose the non-stationary signal into several stationary characteristics of IMF, each IMF can be linear or nonlinear. In order to obtain reasonable instantaneous frequency and, the IMF component has two requirements [8]: *1)* In the whole data set, the number of the extreme point and the number of zero-crossings must be different or at most by one. *2)* At any point, by the local maxima and local minima defined envelope average to zero. The mathematical model can be expressed as follow:

$$\mathrm{S(t)} = \sum_{j=1}^{n} C_j(t) + r_n(t) \tag{1}$$

Where S(t) as the original signals; $C_j(t)$ for the different frequency IMF component signal; $r_n(t)$ is residual signal.

As can be seen from the formula, different IMF component represents the different characteristics of the scale composition, and the IMF component will change along with the original signal change, which contains the frequency from high to low component of signal[9]. These IMF components and a residual term constitute the original signal.

B. Extract The Feature Vector Of Energy

When the gear box fault occurs, the vibration energy will also change, make full use of the energy spectrum of vibration signal, judging gear fault and cause, degree and category further.

EMD decomposed eigen functions IMF respectively represent the stationary signal a group of characteristic scale, the energy change of each frequency band represent the fault condition of gear, therefore, selects the energy feature vector of each scale IMF can be used as a fault judgment. Specific steps are as follows:

*1)*Decompose fault vibration signal of normal gear by EMD, obtained several IMF components.

*2)*Calculate the total energy of each IMF componentE_{ck};

$$E_{ck} = \int |C_k(t)|^2 dt = \sum_{j=1}^{n} |C_{kj}(t)|^2 \quad (2)$$

Where, C_{kj}（j=1,2,3,……）represent the amplitude of signal, the k as which one layers has decomposed, and j for the discrete points of the current layer.

*3)*Based on the result above, combine with the energy changes in each IMF component signal, extract and construct the feature vector. The feature vector construction formulas T and the results are as follows:

$$\mathrm{T} = [E_{c1}, E_{c2}, \dots\dots E_{cN}] \quad (3)$$

In the formula, N represents EMD decomposed the number of layers. In addition, considering the high energy will highlight the individual elements of the numerical result, thus will effects of extraction of signal feature information, therefore need to do the normalization of T, get T'as follows:

$$\mathrm{E} = \left(\sum_{k=1}^{N} |E_{ck}|^2\right)^{\frac{1}{2}} \quad (4)$$

$$T' = \left[\frac{E_{c1}}{E}, \ \frac{E_{c2}}{E}, \dots\dots \frac{E_{cN}}{E}\right] \quad (5)$$

4) Through repeated experiments and data collection to establish feature vector.

C. *OHF Elman Neural Network*

OHF Elman artificial neural network is a dynamic feedback network, has the input nodes for signal input and the output nodes for weighting signal calculation. Compared with BP neural network, OHF Elman has a special link unit called context nodes; and compared with Elman, it has two context nodes. Context nodes memory the output value that output from a moment before hidden nodes unit by receiving feedback signal from hidden nodes, at the same time context2 nodes receives feedback of the output nodes in the second layer, before they input to the hidden nodes the neurons of the context nodes need to delay and storage. So it can enhance the sensitivity to historical data, strengthen the ability of analysis their own information[11]. The structure shown in Figure 1.

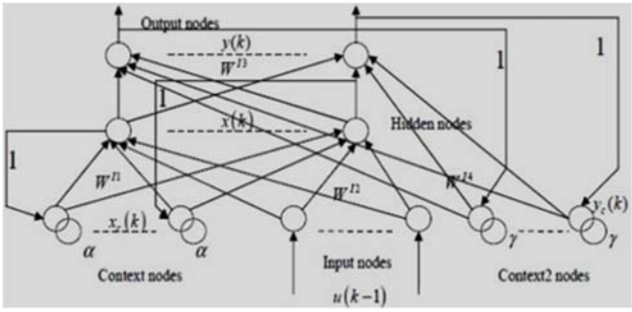


Figure 1. Schematic Diagram of OHF Elman Neural Network

The mathematical model of OHF Elman neural network [10]:

$$\mathrm{x(k)} = \mathrm{f}(W^{I1}x_c(k) + W^{I2}u(k-1)) \quad (6)$$

$$x_c(k) = \alpha x_c(k-1) + x(\mathrm{k}-1) \quad (7)$$

$$y_c(k) = \gamma y_c(k-1) + y(k-1) \quad (8)$$

$$y(k) = g\left(W^{I3}x(k) + W^{I4}y_c(k)\right) \quad (9)$$

Among them, W^{I1} is the connection matrix between the hidden nodes and the undertake nodes, W^{I2} is the connection matrix between the input nodes and the hidden nodes, W^{I3} is the connection matrix between the output nodes and the hidden nodes,W^{I4} is the connection matrix between the output nodes and the hidden nodes.$x_c(k)$ and $x(k)$ respectively represent the output of the undertake nodes and hidden nodes, $y_c(k)$, $y(k)$ represent output of context2 nodes and output nodes, $0 \le \alpha < 1$ is self connect feedback gain factor, g(.) as a linear combination of the hidden nodes output, is the transfer function of output neurons. g(.) usually selects linear function, f(.) uses sigmoid function, as follows:

$$\mathrm{f(x)} = 1/(1 + e^{-x}) \quad (10)$$

Generally, OHF Elman artificial neural network weights modification selects BP algorithm for ranking, using square error and function confinement index, as:

$$\mathrm{E(p)} = \sum_{k=1}^{m} [y(p) - t_k(p)]^2 \quad (11)$$

Where, $t_k(p)$ is the expected value of the output.

III. EXAMPLES OF VERIFICATION

A. *Subway Gearbox Test Bench.*

Compared to other vehicles, gear box rail vehicle with long working hours, the operation cycle is short, and most of the subway transport is overload, so gears are broken easily and need higher equipment repair cost and so on. Strengthen the research of fault diagnosis for gearbox of subway vehicle is urgency and significant.

As shown in Figure 2， the gear box test was designed according to the subway gear box transmission , all components are imported from Germany, so it can simulate the subway gear box working condition perfectly . By the test of MDR-80 mobile data recording system, this system has high testing precision and anti-interference ability.

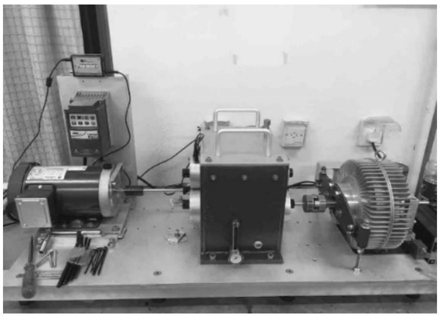
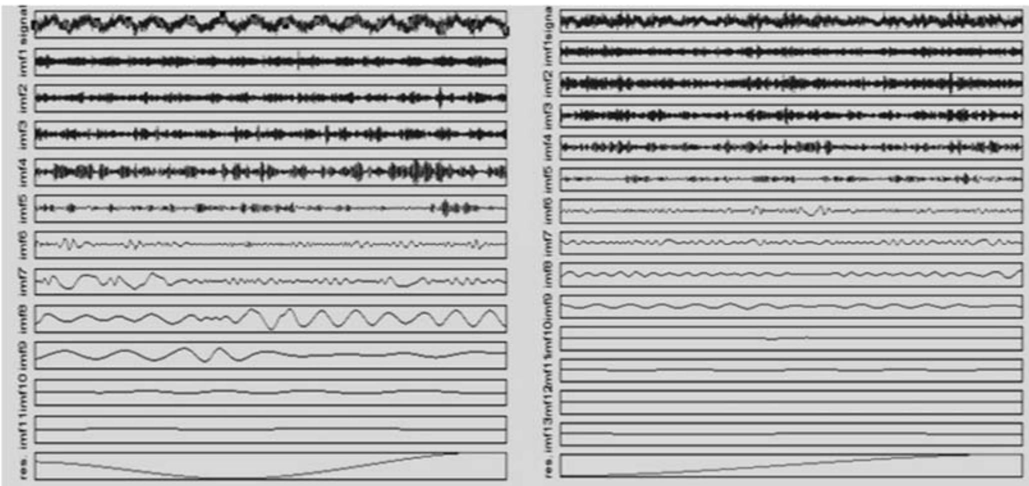


Figure 2. Subway gearbox test bench

B. Analysis of Fault Signal



a. Good Gear b. Break Tooth Gear

Figure 3. IMF of Gear Signal

The original time domain signal of subway gear box test is shown in Figure 4, 'a' is the original normal gear vibration waveform, 'b' for the original vibration waveform of broken teeth gear. Then decompose the original vibration signal based on EMD and obtain 6 IMF components respectively, the results are shown in figure 4. After extract the feature vector from IMF components, get the results shown in table 1. And the OHF Elman neural network test data shown in table 2. There are 8 input, 8 hidden node, and 2 output correspond to 2 gears vibration signal respectively.

After the training of the OHF Elman neural network, the test data of good or tooth break gear vibration signal is shown in Table 3, the test data is ideal, we can distinguish the gear faulteasily.Therefore, this method is positive for fault diagnosis of gear vibration signal.

TABLE 1. CITY SUBWAY GEAR BOX FEATURE VECTOR OF SAMPLE DATA

	Training Sample	Fault Status	Fault Vector
1	0.1163 0.5867 0.6963 0.1854 0.3156 0.1293 0.0285 0.0132	normal	（1 0 0）
2	0.1796 0.2967 0.5123 0.4302 0.6181 0.1514 0.0810 0.0172	normal	（1 0 0）
3	0.0115 0.1394 0.8921 0.4210 0.2590 0.0401 0.0212 0.0037	normal	（1 0 0）
4	0.0597 0.2871 0.9104 0.2793 0.1771 0.0804 0.0156 0.0021	tooth break	（0 0 1）
5	0.4123 0.8001 0.4359 0.0762 0.0547 0.0423 0.0135 0.0054	tooth break	（0 0 1）
6	0.0313 0.0716 0.9640 0.2139 0.1672 0.1003 0.0234 0.0071	tooth break	（0 0 1）

TABLE 2. THE TRAINING TATA

	Training Sample	Fault Status	Fault Vector
1	0.1349 0.2011 0.2987 0.3541 0.8392 0.1716 0.0325 0.0067	normal	（1 0 0）
2	0.2412 0.5015 0.5496 0.4023 0.5093 0.1013 0.0137 0.0172	tooth break	（0 0 1）

TABLE 3. OHF ELMAN NEURAL NETWORK TRAINING RESULTS

Fault Status	Fault Vector	Actual Outputs	Testing Results
normal	（1 0 0）	（0.9651 0.0097 0.0102）	normal
tooth break	（0 0 1）	（0.0056 0.0120 0.9832）	tooth break

IV. CONCLUSIONS

This paper presents a subway gear box fault diagnosis method based on EMD and OHF Elman neural network. We makes full use the characteristics of EMD which has strong adaptive and noise reduction ability and OHF Elman has high interaction speed and good robustness, breakthrough to combine them to use for gear fault diagnosis. The method has been proved by experiments that it can be used for gearbox fault signal diagnosis effectively and accurately. This approach has great influence in improving the city traffic equipment safety and reducing cost of vehicle repair. It can be used for vibration signal diagnosis widely. In addition, the analysis of this paper is only for the complete gear and broken teeth gear, the other fault gear, such as crack, wear and so on need to be further studied.

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REFERENCES

[1] DING Kang, LI Weihua, ZHU Xiaoyong. Practical techniques of fault diagnosis for gears and gearboxes[M]. China Machine Press: Beijing, 2005.

[2] Jacek Dybala, Radoslaw Zimroz. Rolling bearing diagnosing method based on Empirical Mode Decomposition of machine vibration signal[J]. Applied acoustics, vol.77, pp.195-203, Mar, 2014.

[3] Norden E. Huang. New method for nonlinear and non-stationary time series analysis; Empirical mode decomposition and Hilbert spectral analysis[J]. Proc. of SPIE. vol. 4056, pp. 197-209, Jan,2000.

[4] Kuan C. M., Hornik K., Whites H. A Convergence Results for Learning in Recurrent Neural Network[J]. IEEE Trans Neural Network. vol. 6, no.2, pp. 420-440, 1994.

[5] Y. J. Li.EMD-based Fault Diagnosis for Abnormal Clearance Between Contacting Components in A Diesel Engine[J]. Mechanical Systems and Signal Processing, vol. 24, no.1, pp.193-210, 2010.

[6] Chien-Cheng Lee. Robust Radial Basis Function Neural Networks[J]. IEEE Translated on System, Man, and Cybernetics, Part B, vol. 29, no.6, 1999.

[7] CHENG Y. CH. Dynamic properties of Elman and modified Elman neural network[J]. Proceedings of the First International Conference on Machine Learning and Cybernetics, Beijing, pp.637-640, Jan, 2002.

[8] M.C. Pan. Using Appropriate imfs for Envelope Analysis in Multiple Fault Diagnosis of Ball Bearings[J]. International Journal of Mechanical Sciences, vol. 69, pp.114-124, 2013.

[9] JIANG Hang, SHANG Chun-yang, GAO Rui-peng. Wheel/rail fault diagnosis method based on EMD and neural network[J]. Journal of Vibration and Shock, vol.33, no.17, pp. 34-38, 2014.

[10] ShiX.H.,LiangY.C.,LeeH.P.,LinW.Z.,XuX.and LimS. P.Improved Elman networks and applications for controlling ultrasonic motors[J].Applied Artificial Intelligence, vol. 18,no.7, pp. 603-629, 2004.

[11] LIU Minna. Application of Modified Elman Neural Network inGearbox Fault Diagnosis System[D]. North University of China, May, 2012.