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Fault Diagnosis of Diesel Engine Based on Energy Spectrum Analysis

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***Abstract*—This paper has studied the application of wavelet package energy spectrum and frequency energy spectrum analysis in the diesel engine fault diagnosis. Extracting the fault features by wavelet package energy spectrum and frequency energy spectrum analysis of the fault angle of fuel supply decreased 2.5° and plug of air filter, then making those as the input character of neural networks and implementing the fault diagnosis. It is concluded that frequency energy spectrum analysis is more strongly of the practicability than wavelet package energy spectrum analysis by comparing the test results.**

Keywords-wavelet packet; energy spectrum; neural networks; fault diagnosis

I. INTRODUCTION

With today's society development of the industrialization level, the diesel engine as a common power mechanical equipment, fault diagnosis has become an important research object in the fault diagnosis research field. Main signals used for the analysis of diesel engine's state are vibration signal, noise signal, pressure signal and temperature signal, etc. In diesel engine fault diagnosis, mainly adopts the vibration signal analysis method, and the methods of vibration signal processing include amplitude spectrum, power spectrum, zoom spectral analysis, energy spectrum analysis, cepstrum analysis and other many kinds analysis methods. Diesel engine in the actual operation, the frequency range is not the same in the energy spectrum of the response from the different components. If the energy spatial distribution of some output signals compared with normal system output changes, can distinguish the frequency band corresponding to the component should be in the abnormal working state. Usually some frequency components significantly inhibited, the band signal energy is reduced, and some components are enhanced, the frequency band energy increase. On the energy spectrum density or power spectral density for the analysis, which can be concluded that all kinds of fault characteristic features, so the energy spectrum analysis on fault diagnosis is practical and feasible[1]. This paper based on the energy spectrum analysis on fault diagnosis, is mainly to the wavelet packet energy spectrum analysis and energy spectrum analysis are compared.

II. WAVELET PACKET ENERGY SPECTRUM ANALYSIS

If the use of wavelet analysis to fault diagnosis of diesel engine, although able to signal the effective time-frequency decomposition, but only on the low frequency band signals decomposition effect is good, the high frequency frequency resolution is poor. Wavelet packet analysis wavelet transform is an improvement of wavelet analysis, it can do further decomposition to the high frequency part for no analysis, is a more accurate analysis method, effectively improves the time-frequency resolution[2]. So here only discuss the wavelet packet energy spectrum analysis method[3].

Steps of Extracting wavelet packet energy spectrum are:

(1) Do wavelet packet decomposition to the sampling signal, this paper adopts four layer wavelet packet decomposition.

(2) on each layer of wavelet packet decomposition coefficients were reconstructed, extracting each frequency band signal on fourth layers, using S_{4i} signify the reconstructed signal of nodes (*4, i*) .

(3) calculation of the frequency band energy

Set S_{4i} corresponding energy is E_{4i} , to seek the total energy of each frequency band signal. It is $E_{4i} = \int \left| S_{4i}(t) \right|^2 dt = \sum_{k=1}^{n} \left| x_{i,k} \right|^2$. where, $x_{i,k}$ is the amplitude of discrete points of reconstruction signal S_{4i} , and n is sampling points the signal. With these energy values to structure feature vector T, $T = \left[E_{41}, E_{42}, \cdots, E_{415} \right]$.

(4) To construct the feature vector. If the each frequency band energy values are larger, then the amount of computation required is large, therefore needs will feature vector is normalized, normalized formula is $S_i = E_{4i} / E$, where, the total energy E expression is $E = sqrt\left(\sum_{i=0}^{15} \left| E_{4i} \right|^2 \right)$.

III. FREQUENCY DOMAIN ENERGY SPECTRUM ANALYSIS

When the diesel engine system is the normal operation, the system's vibration signal with certain frequency spectrum, if the system in a component failure occurs, with the vibration changes will make the original vibration composition changes, corresponding to its spectrum will have change[4]. Energy spectrum described signal energy along the frequency axis distribution, frequency domain energy spectrum expression is $E = |fft(x(t))|^2$.

The specific method is, this paper adopted the data after reduced frequency, the sample frequency is 10KHz, after FFT transform analysis frequency is 5000Hz. So is will 0 Hz ~ 5000 Hz frequency domain is divided into N bands, separately calculate the each frequency band energy. When the energy is larger, corresponding to the energy of each frequency band value is relatively large, so in order to calculate conveniently, need to put all the energy values for the normalized. Normalized formula is $a_i = \dfrac{a_{\max} - a_i}{a_{\max} - a_{\min}}$

Where, a_i is the each frequency band energy value, $a_{\max}$ expressed the maximum value in a_i, $a_{\min}$ is the minimum value in a_i. Normalized values can be used as feature value required diesel engine fault diagnosis.

IV. Application of Neural Networks in Fault Diagnosis

The nature of the fault diagnosis is through the fault symptom conclude fault reason, and the artificial neural network is through to simulate the infer function of human brain to fault diagnosis, and can through the adaptive learning and adjusting the network size, to achieve pattern recognition and feature extraction. Currently main neural network used in fault diagnosis be the BP network, Elman network and RBF network. Which BP network is a multilayer feed-forward neural network, and because of its simple structure, training algorithm is much, so it has been widely used in practice[5].

The BP network learning process includes forward computation and the error back propagation calculation within network, after all training samples input to neural network to calculate the output of the network. If the data from the output layer is not the desired output, then the network automatically enter the error back propagation, by modifying the weights value and the threshold of each layer neurons, and the error is reduced gradually, in this way, until meet the requirements, then train stop. This paper will be mentioned in the wavelet energy spectrum analysis method and frequency domain energy spectrum analysis of the feature value as the input of neural network, select the number of training samples and test samples, through the training to review output, which testified in front of the feasibility of the proposed method[6].

V. Diesel Engine Fault Diagnosis Example Analysis

In this paper, the experimental data are in the normal operation of diesel engines, artificial set of fuel supply advance angle decreased 2.5 degree and the air filter is clogged two fault, through the acquisition of diesel engine vibration signal to do fault diagnosis. To collecting data the sampling frequency is 40KHz, diesel engine speed is 1500r / min.

First the collected vibration signals preprocessing, then using wavelet packet transform to extract signals feature vector. the vector signal. Using the previously described extracting wavelet packet energy spectrum method, using the db1 of in Daubechies wavelet series do 4 layer wavelet decomposition of signal, a total of 16 frequency bands. Extracting the fourth layer wavelet packet each frequency band energy spectrum scales as the neural network's input vector P, namely *P = [E40 / E, E41 / E, E42 / E, E43 / E, E44 / E, E45 / E, E46 / E, E47 / E, E48 / E, E49 / E, E410 / E, E411 / E, E412 / E, E413 / E, E414 / E, E415 / E]*.

Each condition calculation six samples, set the number of training sample is 12, in which the normal sample number, fault sample number of fuel supply advance angle decreased 2.5 degree and fault sample number of air filter clog all are 4. The test samples were set to 6, normal and two kinds of fault sample number all are 2. Because there are two kinds of failure mode and a normal state, so the network output is expressed as follow, fuel supply advance angle decreased 2.5 degree fault is (1,0,0), the air filter is clogged fault is (0,1,0), the normal state is (0,0,1). The training samples and test samples are shown as Table 7 and Table 1.

TABLE I. Test Samples

Serial Number	**1**	**2**	**3**	**4**	**5**	**6**
E40/E	0.026	0.045	0.037	0.024	0.007	0.011
E41/E	0.044	0.066	0.059	0.062	0.022	0.020
E42/E	0.133	0.151	0.152	0.138	0.046	0.068
E43/E	0.079	0.109	0.131	0.115	0.043	0.059
E44/E	0.129	0.140	0.190	0.150	0.074	0.108
E45/E	0.130	0.114	0.137	0.117	0.058	0.057
E46/E	0.180	0.242	0.243	0.244	0.103	0.111
E47/E	0.231	0.172	0.251	0.218	0.153	0.170
E48/E	0.130	0.114	0.137	0.117	0.058	0.057
E49/E	0.180	0.242	0.243	0.244	0.103	0.111
E410/E	0.566	0.334	0.343	0.412	0.256	0.261
E411/E	0.200	0.173	0.212	0.211	0.106	0.072
E412/E	0.136	0.159	0.215	0.193	0.084	0.093
E413/E	0.173	0.142	0.156	0.165	0.126	0.082
E414/E	0.556	0.678	0.526	0.519	0.859	0.829
E415/E	0.293	0.346	0.437	0.446	0.318	0.380
Ideal Output	100	100	010	010	001	001

Set the input layer neuron number is 16, the output layer neuron number is 3, number of hidden layer neurons is approximately 33, the number of training is 1000, target of the training error is 0.00001, the learning rate is 0.1. After setting up parameters, establishes the BP neural network, and got the training results are shown as figure 1.

From the diagram that the curve of training error can be seen, after 70time after training, the network can achieve our learning goals. Then will the test sample as a neural network's input, to get the test results are shown as Table 2.

From the test results, and we expected output consistent with, can accurate analysis the failures, this method is desirable, but consume time is longer.

Repeat the above, using the wavelet db5 of in Daubechies wavelet series do 4 layer signal decomposition, the same extracting the fourth layer wavelet packet each frequency band energy spectrum scales as the neural network's input vector P, output mode and the above ware same, training samples and test samples used the same calculation method, to train of neural network set up the same parameters, get training results are shown as figure 2.

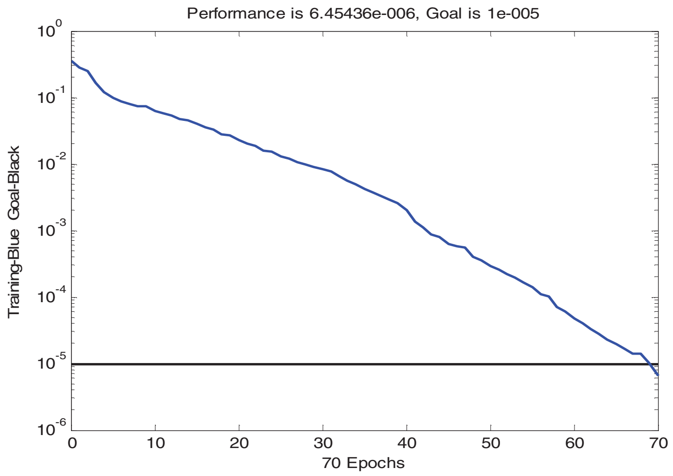

Figure 1. BP neural network error training curve of wavelet packet transform db1

TABLE II. TESTING RESULTS

Sample Output	1	2	3	Testing Results
1	0.9998	0.0000	0.0001	Fuel supply advance angle decreased 2.5°
2	0.9855	0.0001	0.0003	Fuel supply advance angle decreased 2.5°
3	0.0000	1.0000	0.0091	Air filter clog
4	0.0000	1.0000	0.0019	Air filter clog
5	0.0141	0.0000	0.9978	Normal state
6	0.0000	0.0000	1.0000	Normal state

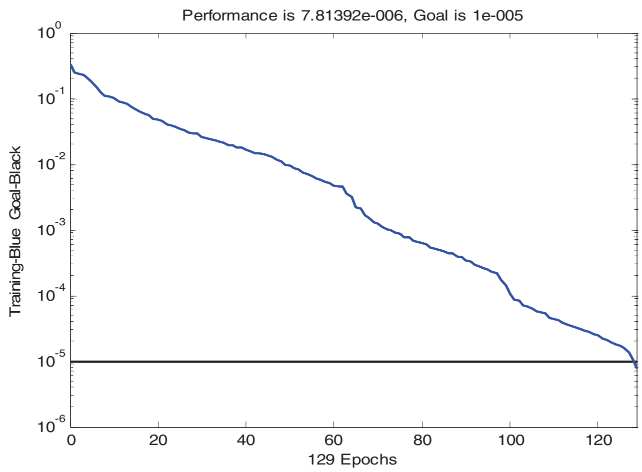

Figure 2. BP neural network error training curve of wavelet packet transform db5

After 129 time training, the error of the network meet the requirements. Then will the test sample as the input of neural network, to get the test results are shown in Table 3.

TABLE III. TESTING RESULTS

Sample Output	1	2	3	Testing Results
1	0.9997	0.0001	0.0004	Fuel supply advance angle decreased 2.5°
2	1.0000	0.0000	0.0000	Fuel supply advance angle decreased 2.5°
3	0.0009	0.5604	0.0002	Air filter clog
4	0.9888	0.9954	0.0000	Can't judge
5	0.0000	0.0228	1.0000	Normal state
6	0.0000	1.0000	0.3913	Air filter clog

From the test results, some value and our ideal output is not consistent, emerged condition of failure error separation, so this method is not desirable.

It is introduced with the frequency domain energy spectrum method to extract the feature vector. This paper uses the data sampling frequency is 40KHz. Because the frequency is too high, so the need to reduce analysis frequency, the reduced frequency is 10 KHz, after done power spectrum the frequency is 5 KHz, will this frequency are divided into 10 band, each band energy be calculated. Choose after normalized energy value S as fault diagnosis feature value, namely the neural network's input vector P, P = [S1, S2, S3, S4, S5, 'S6', S7, S8, S9, S10].

Similarly, each condition selection six samples, set the number of training sample is 12, in which the normal sample number and fault sample number all are 4. The test samples were set to 6, normal and two kinds of fault sample number all are 2. The network output is expressed as follow, fuel supply advance angle decreased 2.5 degree fault is (1,0,0), the air filter is clogged fault is (0,1,0), the normal state is (0,0,1). The training samples and test samples are shown as Table 8 and Table 4.

TABLE IV. TEST SAMPLES

Serial Number	1	2	3	4	5	6
S0	1.000	1.000	1.000	1.000	1.000	1.000
S1	0.934	0.934	0.935	0.935	0.929	0.929
S2	0.867	0.867	0.900	0.900	0.854	0.854
S3	0.474	0.474	0.697	0.697	0.556	0.556
S4	0.790	0.790	0.870	0.870	0.838	0.838
S5	0.867	0.867	0.852	0.852	0.862	0.862
S6	0.154	0.154	0.231	0.231	0.017	0.017
S7	0.000	0.000	0.000	0.000	0.000	0.000
S8	0.810	0.810	0.842	0.842	0.902	0.902
S9	0.764	0.764	0.774	0.774	0.802	0.802
Ideal Output	100	100	010	010	001	001

Set the input layer neuron number is 10, the output layer neuron number is 3, number of hidden layer neurons is approximately 21, the number of training is 1000, training target is 0.00001, the learning rate is 0.1. After setting up parameters, establishes the BP neural network, and got the training results are shown as figure 3.

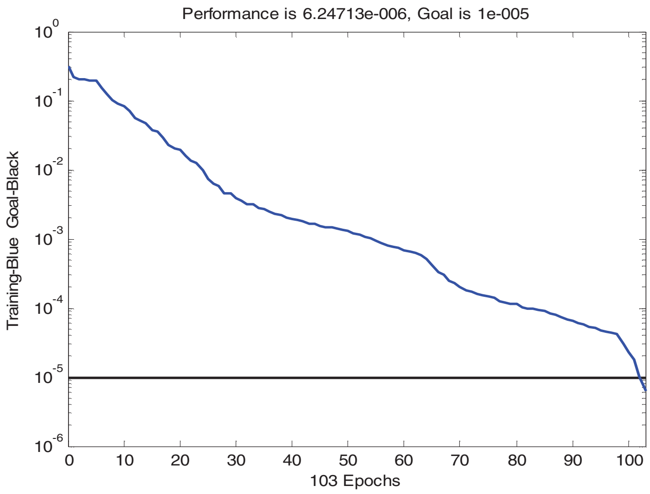

Figure 3. BP neural network error training curve of frequency domain energy spectrum

After 103 time training, the error of the network meet the requirements. Then will the test sample as the input of neural network, to get the test results are shown in Table 5.

TABLE V. TESTING RESULTS

Sample Output	1	2	3	Test Results
1	0.9983	0.0011	0.0012	Fuel supply advance angle decreased 2.5°
2	0.9983	0.0011	0.0012	Fuel supply advance angle decreased 2.5°
3	0.0036	0.9956	0.0003	Air filter clog
4	0.0036	0.9956	0.0003	Air filter clog
5	0.0006	0.0000	0.9998	Normal state
6	0.0006	0.0000	0.9998	Normal state

From the curve of training error, network can rapidly astringe. From the testing results, the fault separation accuracy is relatively high, and the time is short.

Using the three analysis methods to extract feature vector which input to BP neural network, the training time is respectively are shown in Table 6.

TABLE VI. TRAINING TIMES

Analysys methode	wavelet packet transform db1	wavelet packet transform db5	Frequency domain energy spectrum
Elapsed_time	39.5000	73.4540	3.3440

From the above two methods of comparison can be seen, the wavelet packet energy spectrum analysis although can to signal fine time-frequency decomposition, but the wavelet function selection is a difficult problem of the wavelet packet transform. Some can accurately diagnose the fault, but some can not, like the db5 used above. Because the kinds of fault could not only one, so want to choose for each fault are suitable wavelet packet transform is more difficult. Due to the signal decomposition and reconstruction, so the calculation amount is larger, longer time consuming, not suitable for online diagnosis. And the frequency domain energy spectrum analysis method needs less computation amount, shorter time, and the correct rate is higher, thus suitable for online diagnosis.

VI. CONCLUSION

This paper uses wavelet packet energy spectrum analysis method and frequency domain energy spectrum analysis method to the diesel engine vibration signal fault diagnosis, after verification, if the problem of selecting wavelet function can be improved, then the wavelet packet energy spectrum analysis method is a good method of fault diagnosis on the above analysis, the results show the frequency domain energy spectrum method in the practical application is feasible, less time-consuming, accuracy is relatively high.

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TABLE VII. TRAIN SAMPLES

Serial Number	1	2	3	4	5	6	7	8	9	10	11	12
E40/E	0.028	0.038	0.025	0.035	0.031	0.029	0.035	0.043	0.014	0.020	0.019	0.012
E41/E	0.055	0.069	0.034	0.056	0.060	0.055	0.075	0.065	0.024	0.025	0.032	0.025
E42/E	0.148	0.154	0.156	0.120	0.165	0.138	0.127	0.164	0.074	0.076	0.076	0.100
E43/E	0.097	0.125	0.113	0.129	0.133	0.128	0.136	0.121	0.061	0.078	0.074	0.093
E44/E	0.134	0.181	0.117	0.157	0.170	0.124	0.178	0.152	0.105	0.110	0.134	0.108
E45/E	0.099	0.155	0.112	0.170	0.152	0.136	0.143	0.150	0.092	0.105	0.118	0.092
E46/E	0.176	0.226	0.240	0.248	0.224	0.221	0.279	0.239	0.121	0.124	0.176	0.173
E47/E	0.180	0.283	0.163	0.195	0.254	0.256	0.242	0.220	0.229	0.213	0.270	0.265
E48/E	0.099	0.155	0.112	0.170	0.152	0.136	0.143	0.150	0.092	0.105	0.118	0.092
E49/E	0.176	0.226	0.240	0.248	0.224	0.221	0.279	0.239	0.121	0.124	0.176	0.173
E410/E	0.388	0.453	0.634	0.539	0.503	0.459	0.446	0.478	0.264	0.305	0.280	0.463
E411/E	0.155	0.223	0.196	0.245	0.216	0.198	0.200	0.261	0.126	0.112	0.122	0.120
E412/E	0.120	0.161	0.112	0.164	0.212	0.199	0.202	0.160	0.114	0.100	0.128	0.104
E413/E	0.172	0.187	0.147	0.132	0.162	0.194	0.175	0.157	0.114	0.126	0.133	0.104
E414/E	0.683	0.527	0.468	0.508	0.505	0.546	0.508	0.462	0.807	0.777	0.700	0.615
E415/E	0.385	0.311	0.294	0.262	0.290	0.346	0.321	0.401	0.343	0.377	0.436	0.439
Ideal Output	100	100	100	100	010	010	010	010	001	001	001	001

TABLE VIII. TRAIN SAMPLES

Serial Number	1	2	3	4	5	6	7	8	9	10	11	12
S0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
S1	0.957	0.934	0.934	0.934	0.932	0.935	0.935	0.935	0.929	0.929	0.929	0.929
S2	0.919	0.867	0.867	0.867	0.891	0.900	0.900	0.900	0.818	0.854	0.854	0.854
S3	0.731	0.474	0.474	0.474	0.687	0.697	0.697	0.697	0.582	0.556	0.556	0.556
S4	0.895	0.790	0.790	0.790	0.870	0.870	0.870	0.870	0.806	0.838	0.838	0.838
S5	0.910	0.867	0.867	0.867	0.858	0.852	0.852	0.852	0.810	0.862	0.862	0.862
S6	0.168	0.154	0.154	0.154	0.432	0.231	0.231	0.231	0.071	0.017	0.017	0.017
S7	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S8	0.825	0.810	0.810	0.810	0.832	0.842	0.842	0.842	0.824	0.902	0.902	0.902
S9	0.829	0.764	0.764	0.764	0.863	0.774	0.774	0.774	0.793	0.802	0.802	0.802
Ideal Output	100	100	100	100	010	010	010	010	001	001	001	001