Research on Wear Status of Diesel Engine Cylinder Based on BP Neural Network and Instantaneous Speed

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Abstract. The instantaneous speed contains a large amount of diesel engine operating state information. This paper establishes the diesel engine dynamics model to obtain the instantaneous speed curve under different cylinder wear states, and extracts its four dimensionless parameters, then establishes the cylinder wear state model based on BP neural network using the simulated fault signal, and the actual vehicle test data is used to verify. The results show that the cylinder wear analysis model based on BP neural network can accurately determine the cylinder wear state.

1. Introduction

The wear of cylinder is one of the main indicators to judge the technical state of diesel engine. It is difficult to monitor the wear condition of the cylinder quickly and effectively. To extract the cylinder liner wear characteristics from the surface vibration signals measured from the diesel engine, an improved adaptive EEMD method is proposed[1]. 6 parameters including peak-to-peak value and absolute average value were selected as diagnostic parameters and diagnostic model was built[2]. Based on the classic Archard wear model, using the response surface method, wear experimental results under different load conditions were fitted to get the wear correction coefficient model, and cylinder liner wear parts model under conditions of dynamic load was built up[3]. This paper extracts its four dimensionless parameters from the instantaneous speed to train cylinder wear state model based on BP neural network, which has good results.

2. Simulation Analysis of Instantaneous Speed of Diesel Engine

2.1. Establishment of Dynamic Analysis Model of Diesel Engine

The fluctuation of the instantaneous speed is determined by the gas pressure in the cylinder and the reciprocating inertia force. The fluctuations have a good periodicity when the cylinders work exactly the same. The waveforms of the cylinders are similarity under normal condition, while the cylinder pressure is lower than the normal cylinder due to air leakage in the condition of a worn cylinder, so that the torque acting on the crankshaft is periodic, and the rotational angular velocity of the crankshaft exhibits non-uniformity. This paper takes the 12V150ZLC diesel engine as an example, establishes the dynamic analysis model of diesel engine based on GT-crank to study the law of instantaneous speed of diesel engine under different wear conditions. The model is shown in Fig 1. Set parameters such as piston, connecting rod, crank pin, journal, flywheel, etc. The crankshaft is set to 12 cylinders and 4 strokes, the specification is set to load mode, and the firing order and interval angle are
set. The firing sequence of diesel engine cylinder is shown in Fig.2, the cylinders of left row are represented as L1~L6, and the cylinders of right row are represented as R1~R6.

Fig.1 Dynamics model of diesel engine

Fig.2 Firing sequence of diesel engine cylinder

2.2. Analysis of instantaneous speed fluctuation

The state injection method is used to study the correspondence between the instantaneous speed and the cylinder pressure state. The cylinder pressure curve of the wear cylinder is injected into the model, to obtain the simulation signal of instantaneous speed under 4 states (the normal state, sin-cylinder state, neigh-cylinder state and far-cylinder state). In this paper, 1400r/min is taken as an example. Set the normal state, the L3 cylinder (sin-cyl) wear state, the L3 cylinder and R4 cylinder (neigh-cyl) wear state and the L3 cylinder L6 cylinder (far-cyl) wear state separately to simulate the instantaneous speed, the comparison result is shown as Fig.3.

Fig.3 Comparison of instantaneous speed fluctuations between different wear states and normal states

It can be seen from the figure that the power stroke of each cylinder corresponds to the rising interval curve of the instantaneous speed peak. The curve has a regular variety between the different worn state and the normal state. Compared with the normal state, the speed increase rate decreases and
the fluctuation of instantaneous speed increases under the sin-cylinder wear state; the speed increase significantly decreases and the instantaneous speed increases obviously under the neigh-cylinder wear state; the parameters are more obvious under the far-cylinder wear state. The reason is that, the cylinder pressure caused by the worn cylinder decreases, which leads to lower power during the work of the cylinder, while the normal cylinder can provide more power during the work, the normal cylinder may damage due to the large load in long time.

2.3. The extraction of instantaneous speed fluctuation characteristic

Obviously, the increment of the rotation speed of each cylinder is not equal due to the work of the gas pressure when the cylinder is worn, and the amplitude of the crank angle of the acceleration end also changes. From the analysis of the instantaneous speed waveform, the curve trough position represents the torque balance point, and the phase can reflect the cylinder pressure. The average angular acceleration of the acceleration section is proportional to the cylinder pressure torque. Therefore, we select the four parameters to reflect the characteristic of instantaneous speed. These parameters are as follow.

1. Maximum speed increment \( \Delta n_{i,\text{max}} = n_{i,\text{max}} - n_{i,\text{min}} \);
2. acceleration time \( \Delta \theta_{i,\text{acc}} = \theta_{i,\text{acc,max}} - \theta_{i,\text{acc,min}} \);
3. the phase between valley and top dead center \( \Delta \theta_{i,\text{g}} = \Delta \theta_{i,\text{acc,min}} - 60(i - 1) \);
4. average angular acceleration \( \Delta \alpha_i = \Delta n_{i,\text{max}} / \Delta \theta_{i,\text{acc}} \).

In the formula, \( n_{i,\text{max}} \) represents the maximum speed value of the \( i \) cylinder; \( n_{i,\text{min}} \) represents the minimum speed value of the \( i \) cylinder; \( \theta_{i,\text{acc,max}} \) represents the crank angle corresponding to the maximum speed of the \( i \) cylinder; and \( \theta_{i,\text{acc,min}} \) is the crank angle corresponding to the minimum speed of the \( i \) cylinder.

![Comparison of dimensionless parameters of each cylinder](image)

The four characteristic parameters are dimensionless to obtain four dimensionless parameters, separately named the volatility of maximum speed increment \( P_1 \), the volatility of acceleration time \( P_2 \), the phase volatility \( P_3 \), and the average angular acceleration volatility \( P_4 \).
(\(P_2\)), the volatility of the phase between valley and top dead center(\(P_3\)) and the volatility of average angular acceleration(\(P_4\)). The calculation formula is

\[
P_j = \frac{\Delta x_n}{\frac{1}{N} \sum_{i=1}^{N} x_i}
\]

In the formula, \(\Delta x_n\) is the characteristic quantity of each cylinder; \(N\) is the number of cylinder.

The dimensionless parameters of each cylinder in several states are shown as Fig.4.

Fig.4(a) shows the trend of the maximum speed increment volatility of each cylinder, and Fig.4(b) shows the trend of the acceleration time volatility of each cylinder. In the figure, the maximum speed increment volatility and acceleration time volatility are significantly reduced on the worn cylinder; Fig.4(c) shows the volatility of the phase between valley and top dead center, the torque balance point delays due to the decrease of the cylinder pressure, and with the instantaneous speed increment start phase increasing, the volatility become bigger. Fig.4(d) shows the angular acceleration volatility of each cylinder, the volatility is lower than normal cylinder due to the proportional between the angular acceleration and the cylinder pressure torque. The characteristic parameters of the worn cylinder are obviously different from the normal cylinder, which proves that the selected characteristic parameters can effectively identify the worn cylinder, it has certain guiding significance for the worn diagnosis of diesel engine.

3. Real vehicle instantaneous speed analysis

3.1. Acquisition of real vehicle signals

The 12V150ZLC diesel engine is a four-stroke diesel engine with a crankshaft rotation for two cycles during one working cycle. Since the instantaneous speed signal processing is usually carried out in one working cycle, this paper uses the top dead center signal of the diesel engine to intercept the instantaneous speed signal. When performing signal analysis, only the instantaneous speed signal within one duty cycle is usually processed. In order to facilitate signal analysis, this paper uses the top dead center signal of the diesel engine to intercept the instantaneous speed signal.

Fig.5  Instantaneous speed fluctuation curve at each speed

Fig.5 shows the instantaneous speed of the tank diesel engine when the speed is stable at 1200r/min, 1300r/min, 1400r/min and 1500r/min. It can be seen from the figure that there are 12 peaks and troughs at each speed, which exhibits a certain fluctuation law. A peak with a small rise amplitude
appears near 300°CA (the top dead center of R5 cylinder) at 1200 r/min, which may cause by the longer ignition delay at this cylinder. There is no combustion near the position of the dead center, and the instantaneous rotation speed is slightly increased due to the compression pressure of the cylinder.

3.2. The extraction of Real vehicle signal characteristic parameters

According to the previous section, we calculate parameters of real vehicle signal shown as Fig.6. The following assumptions are made in order to analyse the state of cylinder: In the case of normal explosion of each cylinder, if the volatility of the phase difference between the trough and the top dead center is 1.2 times or less than the average, and the other three characteristic parameters are 0.8 times or more than the average, the cylinder is considered to be in good condition; If two or more of the four characteristic parameters do not meet the factor, the cylinder is considered to be a potential wear cylinder.

It can be seen that the volatility of each characteristic parameter are obvious at 1200 r/min, and the phase between valley and top dead center of L5 cylinder is negative. This is because the R5 cylinder lags out, causing the valley phase to cross the next cylinder top dead center, which is consistent with the previous analysis. According to previous rules, the L1 cylinder is considered to be a potential wear cylinder at 1300 r/min, the R1 cylinder is considered to be a potential wear cylinder at 1400 r/min, and the L6 cylinder is considered to be a potential wear cylinder at 1500 r/min.

4. Analysis of cylinder wear state based on BP neural network

4.1. Establishment of cylinder wear state model

Before using the neural network for diagnosis, the appropriate characteristic parameters must be obtained as the input vector (learning sample) of the network. Four dimensionless parameters obtained from sin-cylinder wear simulation are selected as input vectors. Table 1 lists the characteristic vectors and category. Among them, the corresponding categories of the normal cylinder and the potential wear cylinder is 0 and 1, respectively.
Table 1  Characteristic vectors and categories of training samples

| Training samples | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   |
|------------------|------|------|------|------|------|------|------|------|------|------|------|------|
| \( P_1 \)        | 1.080| 0.985| 0.930| 1.087| 0.764| 1.075| 1.069| 0.986| 0.904| 0.928| 1.061| 1.131|
| \( P_2 \)        | 1.031| 0.992| 0.968| 1.041| 0.927| 1.027| 1.027| 0.989| 0.958| 0.968| 1.020| 1.051|
| \( P_3 \)        | 1.062| 1.135| 1.207| 1.087| 1.231| 0.99  | 0.869| 0.942| 1.014| 0.99  | 0.821| 0.652|
| \( P_4 \)        | 1.051| 0.995| 0.963| 1.047| 0.827| 1.049| 1.043| 0.999| 0.946| 0.96  | 1.043| 1.078|
| Category         | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |

The pattern classifier uses a 3-layer BP neural network. The characteristic vector is 4 dimensions and the number of output layer units is 1. The expected error of the network training is set to 0.00001, and the network is trained by the steepest drop BP algorithm (traind training function). Finally, the network training meets the accuracy requirements after the 228th iteration.

4.2. Dentification of Cylinder Wear Analysis Model

After successful network training, real vehicle signals at 4 speeds were selected to obtain the characteristic parameters as test samples. The neural network identification results are shown in Table 2 to Table 5. It can be seen that the model can correctly judge its state. It is obvious that it is feasible to use the BP neural network to detect the cylinder wear state by using the four dimensionless characteristic parameters.

Table 2  Actual output of neural network at 1200r/min

| Test sample | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   |
|-------------|------|------|------|------|------|------|------|------|------|------|------|------|
| \( P_1 \)   | 1.686| 0.619| 1.33 | 0.973| 0.708| 0.292| 0.808| 1.566| 1.319| 0.905| 0.932| 0.861|
| \( P_2 \)   | 1.081| 0.824| 0.886| 0.893| 1.11 | 1.002| 0.853| 0.828| 1.522| 0.748| 1.027| 1.225|
| \( P_3 \)   | 0.686| 1.204| 1.396| 0.855| 1.204| -0.072| 0.554| 1.432| 0.722| 1.408| 1.312| 1.299|
| \( P_4 \)   | 1.515| 0.73  | 1.458| 1.058| 0.62 | 0.283| 0.92  | 1.837| 0.841| 1.175| 0.882| 0.682|
| Output      | 0    | 0.134| 0    | 0.002| 0.012| 0.982| 0.016| 0    | 0.001| 0.001| 0.003| 0.007|
| Identification | 0    | 0    | 0    | 0    | 0    | 1    | 0    | 0    | 0    | 0    | 0    | 0    |
| Actual      | 0    | 0    | 0    | 0    | 0    | 1    | 0    | 0    | 0    | 0    | 0    | 0    |

Table 3  Actual output of neural network at 1300r/min

| Test sample | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   |
|-------------|------|------|------|------|------|------|------|------|------|------|------|------|
| \( P_1 \)   | 0.82 | 1.11 | 1.029| 1.13 | 0.896| 1.101| 0.851| 1.024| 0.718| 1.216| 0.794| 1.312|
| \( P_2 \)   | 0.924| 1.025| 1.064| 1.129| 0.95 | 0.992| 0.95  | 0.937| 0.855| 0.992| 1.015| 1.168|
| \( P_3 \)   | 1.01 | 1.106| 1.587| 0.745| 1.491| 0.914| 0.361| 0.361| 1.491| 0.938| 1.996| 1.091|
| \( P_4 \)   | 0.891| 1.087| 0.971| 1.005| 0.947| 1.114| 0.899| 1.097| 0.843| 1.231| 0.786| 1.128|
Output 0.460 0.000 0.003 0.001 0.008 0.001 0.183 0.002 0.993 0.000 0.137 0
Identification 0 0 0 0 0 0 0 0 1 0 0 0
Actual 0 0 0 0 0 0 0 0 1 0 0 0

Table 4  Actual output of neural network at 1400r/min

| Test sample | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|-------------|---|---|---|---|---|---|---|---|---|----|----|----|
| \( P_1 \)    | 0.818 | 0.81 | 0.979 | 0.662 | 0.911 | 1.05 | 1.118 | 1.134 | 1.044 | 1.154 | 1.012 | 1.308 |
| \( P_2 \)    | 0.936 | 0.846 | 1.028 | 1.015 | 0.922 | 0.825 | 0.991 | 1.145 | 1.011 | 1.211 | 1.035 | 1.035 |
| \( P_3 \)    | 0.665 | 1.094 | 0.991 | 0.755 | 0.966 | 1.145 | 1.068 | 0.934 | 1.375 | 1.132 | 1.164 | 0.71 |
| \( P_4 \)    | 0.872 | 0.954 | 0.948 | 0.651 | 0.985 | 1.268 | 1.125 | 0.986 | 1.029 | 0.949 | 0.974 | 1.259 |
| Output        | 0.070 | 0.075 | 0.002 | 0.914 | 0.003 | 0.000 | 0.000 | 0.001 | 0.001 | 0.001 | 0.002 | 0.000 |
| Identification| 0 0 0 0 1 0 0 0 0 0 0 0 |
| Actual        | 0 0 0 0 1 0 0 0 0 0 0 0 |

Table 5  Actual output of neural network at 1500r/min

| Test sample | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|-------------|---|---|---|---|---|---|---|---|---|----|----|----|
| \( P_1 \)    | 1.127 | 0.871 | 0.561 | 0.859 | 1.048 | 0.846 | 0.918 | 1.181 | 1.222 | 1.124 | 1.007 | 1.236 |
| \( P_2 \)    | 1.142 | 0.945 | 1.039 | 1.052 | 1.052 | 0.855 | 0.8 | 0.942 | 0.926 | 0.991 | 1.036 | 1.22 |
| \( P_3 \)    | 1.022 | 1.523 | 0.879 | 0.786 | 0.842 | 1.214 | 1.028 | 0.923 | 0.954 | 1.232 | 0.991 | 0.607 |
| \( P_4 \)    | 0.979 | 0.915 | 0.536 | 0.811 | 0.988 | 0.982 | 1.139 | 1.244 | 1.309 | 1.126 | 0.965 | 1.006 |
| Output        | 0 0 0 0 0 0 0 0 0 0 0 0 |
| Identification| 0 0 1 0 0 0 0 0 0 0 0 0 |
| Actual        | 0 0 1 0 0 0 0 0 0 0 0 0 |

5. Conclusion
In this paper, the instantaneous speed curve of diesel engine with different cylinder wear state is obtained by establishing dynamics model of diesel engine. Four dimensionless parameters are selected as the input vector to simulate the signal based on BP neural network, which establishes the cylinder wear state model. The model has been verified at the real vehicle speed signals and has good results.

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