On-Line Sensor Diagnosis of the Diesel Engine Cold Starting Based on RBFNN

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Abstract—Based on the radial basal function neural network (RBFNN) and the OLS arithmetic, an on-line sensor fault detection diagnostic strategy on the diesel engine cold starting is proposed. This diagnostic strategy is conducted by RBFNN. The data of sensor sampling is the input and the sensor faults is the output of RBFNN. Some samples could be trained and studied by RBFNN. The parameters, such as, short circuit, open circuit and the stuck-at fault of the electric current, the voltage and the rotational speed have been made by the RBFNN and the OLS arithmetic. The test results indicate that the sensor fault diagnostic accuracy can reach 95.6%. It is value that this diagnostic strategy could be achieved the IV emissions regulations of China in the diesel engine cold starting cycle and also can be used in the vehicle on board diagnosis system.

Keywords—diesel engine; sensor; neural network; cold start; on board diagnosis

I. INTRODUCTION

All the car should be met the needs of emission III standard in China 2008, and the car should be forcibly to install the OBD for emission IV standard. The cold start condition of engine is an important process which affects the vehicle emission. If the sensors performance has been altered under the cold start condition of engine. The faults and the metrical errors will affect the vehicle emission. So, it is important to diagnose the malfunction of the sensors on-line. There are several sensor malfunction diagnostic technologies such as, hardware redundancy, analytical redundancy, expert system, blurry consequence and nerve network, etc [1], [2], [3], [4]. Based on the RBFNN and the OLS arithmetic, an on-line diagnostic strategy has been put forward. The primary sensor fault detection, such as, electric current sensor, voltage sensor and engine rotational speed sensor under diesel engine cold start condition can be detected. According to the flow chats of on-board fault diagnosis several sub-modules such as the preprocess module and fault diagnosis module have been designed and analyzed.

The on-line diagnostic strategy for sensor has been conducted by RBFNN. The sensor sampling data is the input and the sensor faults is the outputs, the diagnostic strategy can be trained and studied by RBFNN itself. The results show: when the error aim is 1%, the error limitative values of the electric current $\hat{I}(t)$, rotational speed $\hat{n}(t)$ and voltage $\hat{U}(t)$ are respectively $\varepsilon_I = 0.042$, $\varepsilon_n = 0.040$ and $\varepsilon_U = 0.021$. The training errors of the electric current sensor and the rotational speed sensor are more important than the voltage sensor.

II. DIAGNOSTIC STRATEGY ON THE SENSOR MALFUNCTION

Figure 1 is the flow chats of on-board fault diagnosis the signals of sensor are dealt with the preprocess module, and then the errors can be put out by the RBFNN and OLS arithmetic in the malfunction diagnostic module. The error value is compared with the error limitative value, finally, to judge whether the sensors is good condition.

A. The preprocess module

Training difficulty the testing dates should be preprocessed to make the input signals located in 0 and 1 by preprocess module. During the sampling time $t$, the output value of the sensor is $X(t)$, after the standardization, $X_n(t)$. $X_{max}$, $X_{min}$ are respectively the sensor upper and lower limit, namely,

$$X_n(t) = \frac{X(t) - X_{min}}{X_{max} - X_{min}}$$  (1)

The malfunction diagnostic module is comprised with the RBFNN module and OLS arithmetic module.

Figure 2 is the RBFNN module [5]. If there are n sensors to diagnose, n malfunction sub-networks are designed [6]. From Figure 2, $X_1$, $X_2$ and $X_3$ are the electric current sensor, the voltage sensor and the rotational speed sensor of diesel engine. $y_1$, $y_2$ and $y_3$ are the output errors of the sensors.
Figure 2. RBFNN module

Figure 3 is the structure of the predictor on the RBFNN. Every sensor is corresponded to a sub-network, a certain sub-network input signal is defined as the input signals of the other n-1 sensors at “t-1” time except the “i” sensor, the output signal is the forecast value of the “i” sensor at “t” time. The merit of the deal method is: if the “i” sensor is malfunction at “t” time, the malfunction sensor output signal is compensated by the redundancy relation on sensors. Within a sampling time, at first, the output data of the sensors, such as, x (1), x (2),…, x (m) are regarded as the input network stylebook, the “m+1” sensor output data is regarded as the output network stylebook to study on-line, as far as the network convergent value are arrived at the definite extent. Secondly, the sensors output data, such as, x (2), x (3)… x (m+1) are regarded as the network input stylebook to forecast the “m+2” sensor output data. if the result is less than a certain threshold value, then the output data of the sensors, such as, x (2), x (3),…, x (m+1) are regarded as the input stylebook and x (m +2) is regarded as the network output stylebook to study on-line, as far as the result is more than a certain threshold value, the sensor occur the malfunction.

B. Study arithmetic module

To design and train the RBFNN, firstly, the cell number, the center coefficient and the width of the containing cell should be selected. Secondly, the connective coefficient should be selected. The study arithmetic module trains the network, confirms the center and the connective coefficient of the containing cell by OLS arithmetic. The OLS arithmetic regards the RBFNN as the linear recursive model [7]:

\[ d(t) = \sum_{i=1}^{M} p_i(t) \theta_i + e(t) \]  

(2)

In (2), \( d(t) \) is anticipant output. \( \theta_i \) is the parameter. \( p_i(t) \) is recursive arithmetic operator. \( e(t) \) is the error signal. The formula (2) is transformed into the matrix:

\[ d = P \theta + E \]  

(3)

In order to analyze the output value influence brought recursive arithmetic operators, the matrix \( P \) will be analyzed by tricorn positive intersect, \( P = WA \), here, \( A \) is the upper tricorn matrix, \( W \) is the matrix which rows are positive intersected. So the formula (3) is transformed into the follow formula:

\[ d = WA \theta + E \]  

(4)

Figure 4 is the computational process on the RBFNN centre selected by the OLS arithmetic.

III. APPLICATIONS

The test of on-line sensor malfunction diagnosis has been made in the cold start laboratory, the test systematic diagram is Figure 5. It contains diesel engine, electromotor, battery and the sensors, such as, voltage, electric current, rotate speed and temperature sensors. The temperature sensors are inspected by SKE-32AD, the diesel engine is dragged by the electromotor.

The RBFNN is comprised by three subnets, which are respectively made up of diagnosis the malfunctions of the electric current sensor, the voltage sensor and the rotational speed sensor. Figure 6 is the structure of the RBFNN sub-modules. From Figure 6, I, n, U are respectively the sampling value of the electric current sensor, the voltage sensor and the rotational speed sensor, t is the time, \( \hat{I}_t \), \( \hat{n}_t \) and \( \hat{U}_t \) are...
respectively the estimate value of the electric current sensor, the voltage sensor and the rotational speed sensor. The tests are carried under the temperature -25°C, the sampling frequency is 15Hz, and the sampling data are divided into 2112 groups.

\[
\begin{align*}
I(t-1), I(t-2), \ldots, I(2), I(1) & \rightarrow \text{RBFNN}_I \rightarrow \hat{I}(t) \\
n(t-1), n(t-2), \ldots, n(2), n(1) & \rightarrow \text{RBFNN}_n \rightarrow \hat{n}(t) \\
U(t-1), U(t-2), \ldots, U(2), U(1) & \rightarrow \text{RBFNN}_U \rightarrow \hat{U}(t)
\end{align*}
\]

Figure 6. Structure of the RBFNN sub-modules

Figure 7 is the partial sampling data. OLS is acted as the training RBFNN arithmetic, the allowable error of the RBFNN is 0.01, the patulous constant is 1, the maximum initialization nerve cell number is 20. The display frequency is 0.05. Table I is the training errors on three RBFNN sub-modules. Table I shows the error of the electric current sensor is maximal. The error of the voltage sensor is minimal.

Figure 7. Samples of collected training data

<table>
<thead>
<tr>
<th>TABLE I. TRAINING ERRORS OF THE RBFNN SUB-MODULES</th>
<th>current sensor</th>
<th>rotational speed sensor</th>
<th>voltage sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average absolute error</td>
<td>0.0082</td>
<td>0.0091</td>
<td>0.0043</td>
</tr>
<tr>
<td>Average error</td>
<td>2.27×10^{-4}</td>
<td>3.17×10^{-4}</td>
<td>1.44×10^{-4}</td>
</tr>
<tr>
<td>root mean square error</td>
<td>1.72×10^{-4}</td>
<td>1.06×10^{-4}</td>
<td>4.81×10^{-5}</td>
</tr>
</tbody>
</table>

Figure 8 is the training errors of electric current, voltage sensor and rotational speed sensor by the RBFNN. The error training target is 1%, the training error sequences of electric current, voltage and rotational speed sensor are apart \( \varepsilon_I = 0.042 \), \( \varepsilon_U = 0.021 \) and \( \varepsilon_n = 0.040 \).

![Figure 8. Training errors](image)

For the optimal balance of the precision and the credibility, a counter is designed. As the first malfunction of each network is took place by the diagnosis, the counter then is started, the diagnostic malfunction amount (N) is memorized by the counter at a certain time. By constant train and study, N is 9.

IV. EXPERIMENT

The malfunction on the typical sensor is composed by the hard malfunction, such as, short circuit, open circuit and stuck-at fault and the soft malfunction, such as, linear error, sensitive error and repetitious error. In order to validate the diagnostic strategy, the diagnostic tests for detecting the malfunctions of the electric current, rotational speed and voltage sensor have been made in the cold start test laboratory. Table II is the malfunction diagnostic results by the RBFNN. From Table II, the diagnostic rate of the short circuit and the open circuit of the electronic current sensor and voltage sensor are arrived at 100% by the diagnostic strategy. To the stuck-at fault, the malfunction diagnostic accuracy is arrived at 95.6%.the malfunction accuracy on the stuck-at fault of the voltage sensor
is better than that of the electronic current sensor and rotational speed sensor.

<table>
<thead>
<tr>
<th>Function</th>
<th>Diagnostic Outcome on Hard Malfunction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current sensor</td>
<td>Short circuit 100, Open circuit 100, Stuck fault 95.6</td>
</tr>
<tr>
<td>Rotational speed sensor</td>
<td>Short circuit 100, Open circuit 100, Stuck fault 96.4</td>
</tr>
<tr>
<td>Voltage sensor</td>
<td>Short circuit 100, Open circuit 100, Stuck fault 98.3</td>
</tr>
</tbody>
</table>

Figure 9 shows the errors state of electric current, rotational speed, and voltage sensor by RBFNN along with the temperature from -25°C to 0°C. From Figure 9, at temperature 0°C, the diagnostic errors of sensor linear, sensitive, and repetitious are 0%. As the temperature fell down, the error tendency is increased. For example, to the rotational speed sensor, its error is the maximal at -25°C, the linear error is 0.5%, the sensitive error is 0.8%, and the repetitious error is 0.1%. To the voltage sensor, its error is minimum at -25°C, the linear error is 0.4%, the sensitive error is 0.7%, and the repetitious error is 0.08%, all that can be met the performance of sensors in the well-balanced state of diesel engine.

Figure 9. Errors on soft malfunction

V. CONCLUSIONS

(1) Based on the RBFNN and OLS arithmetic, a set of the on-line diagnostic strategy on the sensors malfunction of the cold start system in the diesel engine has been setup. From the experimental data, the neural network have been trained and validated. The result shows the strategy is effective and valuable.

(2) The strategy has been applied to the on-line test. The results show: the diagnostic accuracy can reach 95.6%, the maximal linear error is 0.5%, the maximal sensitive error is 0.8%, and the maximal repetitious error is 0.1%, in test of the cold starting. All these can be met the needs of managing criterion for OBD.

ACKNOWLEDGMENT

This work was supported by National Natural Science Foundation of China under Grant No. 50776042. The contents of this paper reflect the view of the authors who are responsible for the facts and accuracy of the data presented in herein. The contents do not necessarily reflect the official views or policies of Jiangsu University. This paper does not constitute a standard, specification or regulation.

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