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Computational Method of Aging Index for Catalytic Converter Based on Wavelet Transform

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Abstract: In order to control vehicle exhaust emission effectively, the conversion efficiency of catalytic converter is one of the key monitoring and evaluated indexes. The signal monitoring system of oxygen sensor is built by the TI2812 microcontroller. The method is to obtain the eigenvector and correlation coefficient of signal energy distribution, and to determine the two signal correlativity by using the Daubechies wavelet functions to analyze voltage signals of front and back oxygen sensors. The noise and vibration source are identified with the correlation coefficient. The aging level of catalytic converter is estimated according to the value of correlation coefficient. Experiments show that the method is more simple and effective than the traditional one.

Keywords: Automobile, Catalytic converter, Wavelet transform, Correlation coefficient.

1. Introduction

Motor vehicle catalytic converter is the most efficient outside purification technique to meet the discharge standard. But catalytic converter is easy to generate the chemical poisoning, heat aging and mechanical damage, coking carbon deposit and pollution etc during the motor vehicle running. It causes transformation efficiency decrease and catalyst converter fail, and makes engine emission worsen sharply. Therefore, it is necessary to monitor the catalyst efficiency of conversion. Automobile emissions standards have the strict request for engine and vehicle emission pollution in cold starting, and compels vehicle to install on-board diagnosis system (OBD). The key monitoring objects have three indicators, one is whether the conversion efficiency of catalytic converter has decreased or not. One is whether the engine catch fire or not, and another one is the oxygen sensor is degradation or not. Therefore, we require the catalytic converter performance strictly, which both must have high conversion efficiency and good durability.

Transformation efficiency is the main performance indicators of catalytic converter, and which is obtained by monitoring and calculating the concentration of pollutants from the front and back catalyst converter. The method was adopted barely with which measure the concentration of pollutant from engine emission for diagnosis. The relationship between the other sensor (such as oxygen sensor, the temperature sensor) and catalyst conversion efficiency was established and estimated indirectly. At present the catalyst conversion efficiency was monitored with three kinds of methods such as oxygen capacity estimation [1-3], exhaust component analysis and reaction heat analysis [4]. Among them, the methods of catalyst diagnosis based on the ability of storing oxygen were widely used.

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The TI2812 digital signal processor was chosen and the signal monitoring system from oxygen sensor was established in this paper. The voltage signal from the front and back oxygen sensor was obtained. The correlation between the output signal of front and back oxygen sensor was analyzed by wavelet transform method. According to the correlation coefficient of catalytic converter, we can judge the degree of ageing and then evaluate the conversion efficiency.

2. The Monitoring System of Oxygen Sensor

The methods of OBD-II system monitoring catalytic converter efficiency is commonly using the front and back dual oxygen sensor method which is installing an oxygen sensor respectively in the upstream and downstream of catalytic converter, by monitoring upstream and downstream of oxygen sensor signal to estimate the oxygen storage capacity. To get the oxygen sensor signal and the development of electronic control unit, TI2812 digital signal processor is selected as the core to design the data acquisition system of output signal from oxygen sensor which is shown in Fig. 1, mainly including A/D converter, interrupt handling, the SCI serial port, the LabVIEW serial read and data storage, the data acquisition process is shown in Fig. 2.

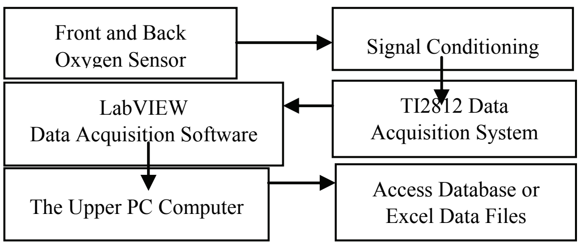

Fig. 1. Acquisition and Monitoring System of Oxygen Sensor Signal

2.1. Program of Receiving Data

TI2812 as lower computer after completing the acquisition of sensor data, the data from host PC were monitored by the RS-232 and the VISA interface of LabVIEW. LabVIEW is used for completing the work of serial read and data storage, the program flow chart is shown in Fig. 3.

The writing of driving program in LabVIEW changes with the difference of drive mode, which makes the versatility and compatibility of the application become poor. In order to solve this problem, NI has developed a convenient and high-level application programming interface what is called VISA for all kinds of instruments bus to communicate. VISA function includes a simple control function set to complete the configuration of the serial port and read the work. In the design, the serial port is configured by the configuration of serial node of VISA and the VISA resource name is COM1, the baud rate is 9600.

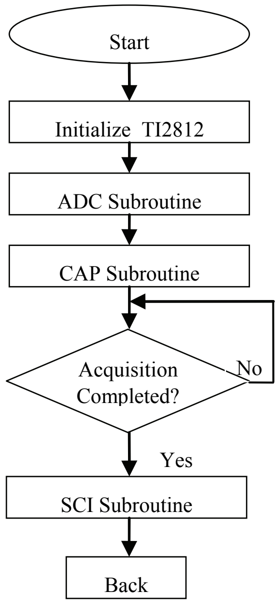

Fig. 2. Data Acquisition Flowchart.

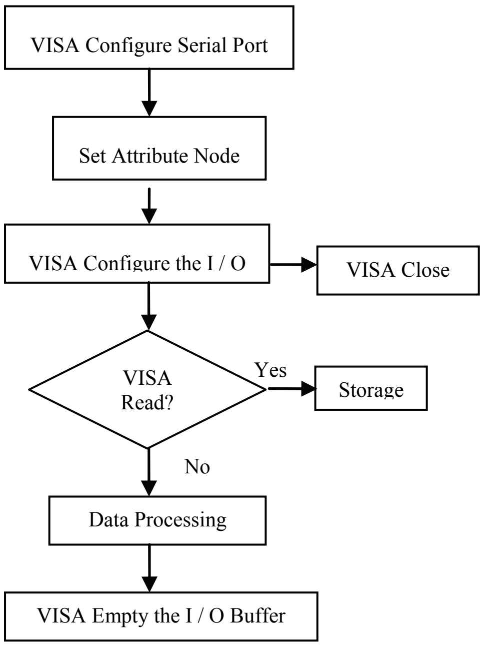

Fig. 3. VISA Read the Serial Flow Chart.

2.2. Data Storage

Factors of affecting the relationship between upstream and downstream oxygen sensor signal include sensor performance, measurement error and interference etc. The sensitivity, stability, noise, and dynamic characteristics of oxygen sensor were compared and analyzed. Multiple measurement method, which can effectively limit or reduce the random error and the larger value of the error should be discarded when the test results are stored, The output voltage of oxygen sensor was up to 1.0 V, low voltage (0.3 V or lower), and RC filter and voltage follower were used in the signal conditioning circuit for reducing interference.

In order to analyze data conveniently, the read data in serial was saved by the LabVIEW program. The data from multi channel into an array using local variables, then the array was converted into strings by the function of string conversion, and the gotten date/time string were connected. Finally the information was written into the text file in order to achieve saving data.

2.3. The Aging Index of Catalytic Converter

A three-way catalytic converter in gasoline engine has many performance indicators. The main performance indicators are pollutant conversion efficiency and exhaust flow resistance. After the exhaust from the motor vehicle engine there is a catalytic reaction in the catalytic converter, and its harmful pollutant concentration obtained reduction in varying degrees. The conversion efficiency of the catalytic converter is defined as:

$$\eta_i = \frac{c(i)_{in} - c(i)_{out}}{c(i)_{in}} \times 100\% , \tag{1}$$

where $c(i)_{in}$ is the concentration of entrance in catalytic converter for exhaust pollutants i, $c(i)_{out}$ is the concentration of outlet in catalytic converter for exhaust pollutant i, The conversion efficiency of a contaminant in the catalytic converter depends on the composition of the contaminants, the activity of a catalyst, the operating temperature, space velocity and other factors. The air-fuel ratio characteristics, the ignition characteristics and airspeed characterization of the catalytic converter are used for the representation of these factors, and the flow resistance of exhaust gas in catalytic converter is used for the representation of flow characterization.

It was supposed that the output signal of upstream oxygen sensor is x (t), the output signal of downstream oxygen sensor is y (t), the current catalytic converter aging index (ID) is defined as [5]

$$\begin{aligned} ID &= Max\left\{\phi_{xy} / \phi_{xx}\right\} \\ \phi_{xx} &= \int x^2(t)dx \\ \phi_{xy} &= \int x(t)\,y(x-\tau)\,d\tau \end{aligned} \tag{2}$$

If the catalytic converters are aging, the maximum value of ID is about 1.0. It indicates that the voltage signal waveforms of two oxygen sensor are similar.

3. The Basic Principle of Wavelet Transforms

Establish the signal $x(t)$ is a square integrable function, $\psi(t)$ is called the function of a basic wavelet or mother wavelet, the wavelet transform of the signal $x(t)$ can be defined as (a>0) (3)

$$\begin{aligned} WT_x(a,b) &= \tfrac{1}{\sqrt{a}}\int_{-\infty}^{\infty} x(t)\psi*\left(\frac{t-b}{a}\right)dt \\ &= < x(t), \psi_{a,b}\ \ (t) > \quad a > 0 \end{aligned} , \tag{3}$$

where a, b are called scale parameter and displacement parameters,* is complex conjugate, $< x, y >$ stands for inner product which means

$$< x(t), y(t) >= \int x(t)y(t)dt \tag{4}$$

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \tag{5}$$

The above equation is the expansion of displacement and scale in the basic wavelet, whose equivalent frequency domain expression is

$$WT_x(a,b) = \tfrac{1}{2\pi}\int\ X(\omega)\Psi*(a\omega)e^{j\omega b}d\omega \tag{6}$$

where $X(\omega), \Psi(\omega)$ are the Fourier transformations of $x(t)$ and $\psi(t)$.

So, if the complex frequency characteristics of $\Psi(\omega)$ is more concentrated band-pass function, wavelet transform has the ability to characterize the local property of signals $X(\omega)$ to be analyzed in the frequency domain. When using different values of ‘a’, the center frequency and bandwidth of $\Psi(a\omega)$ are not the same, but the quality factor[(center frequency)/(bandwidth)] remains the same.So different scales for the wavelet transform is roughly equivalent to a set of band-pass filter processing the signal in the frequency domain.

Mallat has proposed the concept of multi-resolution in the signal processing using filter bank equivalently computing discrete wavelet, so that the calculation method is greatly simplified. Mallat tower algorithm can be described as follows.

For the discrete sequence signal $x(t)$, as follows

$$x^{(0)}_k = x(k) \quad k = 0,1,2,\cdots N-1$$
$$x_k^{(j)} = \sum h^*_{n-2k} x_n^{(j-1)} \quad , \qquad (7)$$
$$d_k^{(j)} = \sum g^*_{n-2k} x_n^{(j-1)}$$

where N is the sampling signal points, $x_k^{(j)}$ is the smooth approximation when resolution is 2^{-j} (the j layer wavelet decomposition), $d_k^{(j)}$ is the detail signal when resolution is 2^{-j} , h_k and g_k are the impulse responses of conjugate mirror filter, Mallat has made a detailed study on its value.

Mallat algorithm is using a set of band-pass filter to filter the signal, in order to decompose the signal into different frequency channels. Suppose the analysis frequency of original signal is f . Firstly the signal is decomposed into the high frequency signal details ([$2^{-1}f, f$]) and low frequency ([0, $2^{-1}f$]) discrete approach signal. Then every time conduct the decomposition, the last decomposition of low-frequency discrete approximation signal is decomposed into sub-high-frequency and low frequency. After each decomposed layer, half the number of data points, double the sampling interval, so the decomposition carry on N times, the wavelet decomposition results of the N layer is obtained.

As the results of the wavelet decomposition of each frequency channel is equivalent to the original signal by filtering and reducing the sampling point in the time domain signal, the signal can be analyzed according to the results in the time domain. But after the minus point sampling of wavelet analysis the temporal resolution is decreased. If improve the calculation accuracy, the results in this frequency channel can be reconstructed to restore the temporal resolution of the original signal.

The reconstruction algorithm can be finished by the following formula, namely

$$x_k^{(j-1)} = \sum_n h^*_{2k-n} x_n^{(j)} + \sum_n g_{2k-n} d_n^{(j)} \qquad (8)$$

The construction and selection of wavelet functions use different principles depends on the purposes of application [6]. In recent years, the selection of wavelet function $\psi(t)$, the wavelet decomposition of function $x(t)$ and the reconstruction algorithm have been made great progress, and a number of general calculation procedures are appear. According to the purpose of calculating aging index, the selection of wavelet function was carried out. The real time voltage signals from front and back oxygen sensor were decomposed and reconstructed by selecting different wavelet function $\psi(t)$ in MATLAB. By comparison and analysis, the Daubechies wavelet function was adopted.

4. Eigenvectors and Correlation Coefficient of the Signal

It is supposed that $x(t)$ is the output signal of oxygen sensor, decompose $x(t)$ in four layers of wavelet, the decomposition is

$$x = a_1 + d_1 + a_2 + d_2 + a_3 + d_3 + a_4 + d_4$$

where a_i, d_i are i layer reconstructed signal of four-layer wavelet decomposition.

Suppose

$$E_{ai} = \int_{-\infty}^{+\infty} a_i^2(t)dt$$
$$E_{di} = \int_{-\infty}^{+\infty} d_i^2(t)dt$$
$$E_{ai} = \left(\sum_1^4 E_{ai}^2 + \sum_1^4 E_{di}^2 \right)^{1/2}$$

Define the characteristics vector of the signal $x(t)$ as [7, 8]

$$T = \left\{ E_{a1}, E_{d1}, E_{a2}, E_{d2}, E_{a3}, E_{d3}, E_{a4}, E_{d4} \right\} / E \qquad (9)$$

It is supposed that $x(t)$, $y(t)$ are output signals of upstream and downstream oxygen sensor, T_x , T_y are the feature vector of the response. Define the correlation coefficient of $x(t)$ and $y(t)$ as

$$R_{xy} = T_x T_y \qquad (10)$$

Correlation coefficient R_{xy} reflects the degree of correlation , which can be used to decide the degree of correlation of the output signals from upstream and downstream oxygen sensor.

5. The Correlation Analysis of Catalytic Converter

The fuel injection is controlled by the output signal from oxygen sensors, to ensure that the air fuel ratio is in theory air-fuel ratio nearly is the main technique in control gasoline vehicles emission [9].The voltage signal from the upstream and downstream oxygen sensor which is collected before and after the purification of automobile exhaust is different. The signal from upstream oxygen sensor changes is smaller, while signal from downstream oxygen sensor changes is larger with the use (aging) time of catalytic converter, which is shown in Fig. 4, Fig. 5 and Fig. 6. It can be seen from Fig. 4 to Fig. 6 that before the aging the catalyst oxygen storage capacity is relatively strong which can release oxygen in the poor oxygen and storing oxygen in the rich oxygen, so that the harmful exhaust gases undergo chemical changes to achieve the goal of purifying the exhaust gas. The corresponding fluctuation-resistant ability is very strong and the downstream oxygen sensor has a relatively long lag time. With the increasing aging time, the catalyst oxygen storage capacity decreased, resistance to fluctuations in the capacity dropped, the lag time of the downstream oxygen sensor shortened, the amplitude of the dynamic response of the downstream oxygen sensor and the output cycle will gradually close to the upstream oxygen sensor[10]. Thus, by comparing the output waveform of front and back oxygen sensor of catalytic converter, it can determine the catalytic converter's oxygen storage capacity and the degree of the aging of the catalytic converter is obtained which is through the analysis of correlation of the output waveform of front and back oxygen sensor to determine the performance of the catalytic converter.

The output waveform of front and back oxygen sensors is stored as discrete data which is acquainted in the monitoring system. The information of each band can be gotten using the wavelet transform, using the feature vectors of the energy element constructors formula (9), after obtaining the feature vectors directly calculate the correlation coefficient of front and back oxygen sensor in accordance with the formula (10), then the correlation analysis of front and back oxygen sensor is completed. The data from front and back oxygen sensor in a fresh state was selected for analyzing. The results of wavelet analysis are shown in Fig. 7, Fig. 8, the calculated correlation coefficient is shown in Table 1.

The method of dual oxygen sensor was used to judge the performance of catalytic converter. As a matter of fact, that is the detection of oxygen storage capacity of catalytic converter. The one which has a strong oxygen storage capacity has higher conversion efficiency. The method of wavelet transform described earlier can be used to obtain the correlation the front and back oxygen sensor under different aging state, which is shown in Table 1. The greater correlation, the waveform of front and back oxygen sensor is the closer and the degree of aging of the catalytic converter is the higher [11].

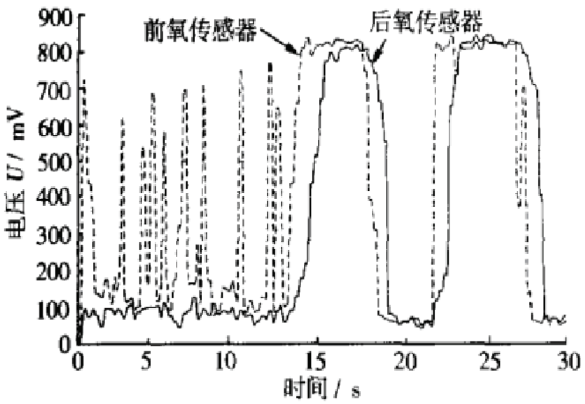

Fig. 4. Output Signal in Fresh state.

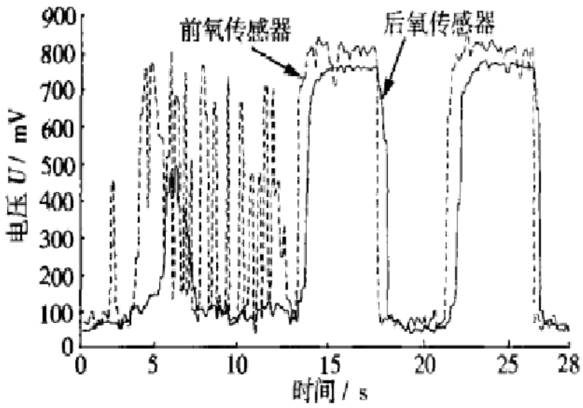

Fig. 5. Output Signal after Aging an Hour.

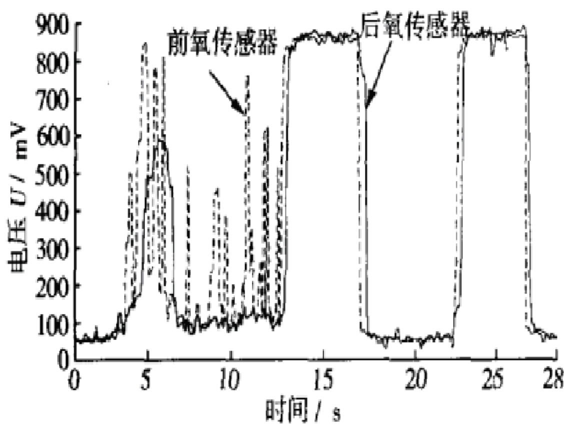

Fig. 6. Output Signal after Aging b Hour.

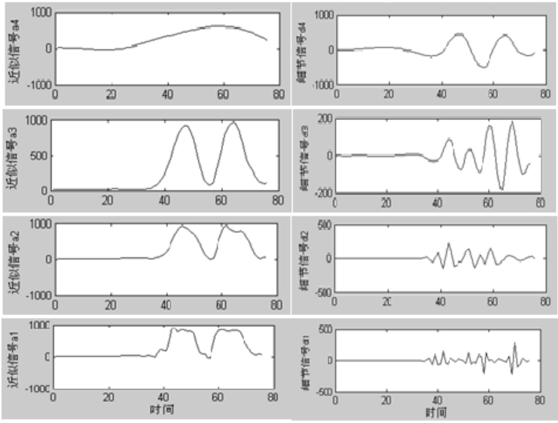

Fig. 7. Reconstructed Signal of the front Oxygen Sensor.

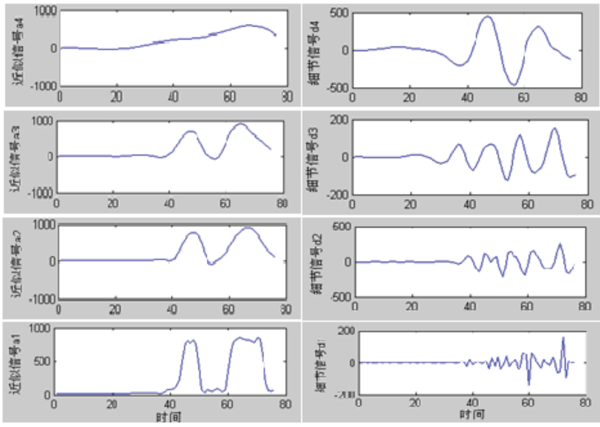

Fig. 8. Reconstructed Signal of the back Oxygen Sensor.

Table 1. The Feature Vector and Correlation Coefficient in Different Aging Degree.

The Degree of Aging	Feature Vector	Correlation Coefficient
Fresh	T_1=[0.283,0.486,0.322,0.219,0.022,0.009,0.029,0.023]	0.876
	T_2=[0.423,0.510,0.505,0.375,0.012,0.078,0.026,0.066]	
After a hour	T_1=[0.330,0.186,0.116,0.070,0.016,0.100,0.041,0.004]	0.968
	T_2=[0.514,0.210,0.129,0.083,0.011,0.114,0.048,0.004]	
After b hour	T_1=[0.383,0.243,0.156,0.081,0.015,0.025,0.033,0.011]	0.994
	T_2=[0.399,0.304,0.187,0.112,0.022,0.019,0.036,0.012]	

6. Conclusion

1) The signal monitoring system of oxygen sensor is built based on TI2812 microcontroller. The voltage signal of front and back oxygen sensor can be collected real time and effectively. The analysis data were supplied in order to evaluate the efficiency of catalytic converter.

2) The theoretical analysis and experimental verification shows that using the four wavelet decomposition gets feature vectors of the energy distribution from front and back oxygen sensor signal. The correlation between the front and back oxygen sensor signal is studied based on the correlation coefficient of the signal energy distribution. The calculating method of aging index of catalytic converter which can be evaluated by the correlation coefficient is given. It is more simple and effective using the method in the evaluation of catalytic converter aging than the traditional analysis method.

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