Detection of engine misfire by wavelet analysis of cylinder-head vibration signals

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Abstract: The misfiring fault of internal combustion engine was detected by using the vibration signals of cylinder-head. Based on the data acquisition system built with LabVIEW, the cylinder-head vibration signals were detected with an accelerometer while the engine was rapidly accelerating from idle speed to high speed, at which time the engine was running under four working conditions of normal and single cylinder misfiring, double cylinders continuously misfiring and double cylinders alternately misfiring. After decomposing the vibration signals with db3 wavelet, whether the engine was misfiring or not, and what type of misfiring, were judged by comparing the decomposing results. The resultd showrf that, the low-frequency vibration of the engine cylinder head was related to the rotation of the principal shaft, and the high-frequency vibration was related to the combustion in the cylinder. There were certain corresponding relationships between wave crests of high-frequency vibration and wave crests of low-frequency under the four conditions of normal and faults when engine runs in idle segment, accelerating segment, and high-speed segment. Thus, the misfiring fault and type can be detected by analyzing the corresponding relations. Detection of the misfiring fault by using wavelet analysis was effective and feasible.

Keywords: internal combustion engine, acceleration, multiple misfiring, wavelet analysis, LabVIEW

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1 Introduction

Misfiring fault is one of the most familiar faults of internal combustion engine (I.C.E.). Effective detection method of misfiring fault is necessary for the design of new cylinder shapes and the configuration of a reliable calibration program for engines.

There are many approaches to detect engine misfiring fault today which are shown as follows. The first approach is to detect misfiring by making use of ionic current (I.C.). That is, to use the spark plug as the sensor and to identify the misfiring cylinder by the change of ionic current between the electrodes of the spark plug when the cylinder is working[1,2]. The second one is to detect misfiring by the waveform of ignition voltage (W.I.V.). That is, to diagnose the fault based on the difference of ignition voltage waveforms of a spark plug in different working conditions[3]. The third one is to detect misfiring by the engine cylinder pressure (E.C.P.). That is, to calculate the indicated mean effective pressure (I.M.E.P.) by measuring the pressure in engine cylinders and to compare with that of normal condition[4-6], and the fault can be recognized from the result. The fourth one is to detect misfiring by the oxygen contained in exhaust gas (O.C.E.G). That is, to measure the oxygen density at the end of the exhaust pipe in the engine. The higher the oxygen density than that of normal working conditions indicates a misfiring fault in the engine[7]. The fifth one is to detect misfiring by the rotation speed of the crankshaft (R.S. C.). That is, to establish the linear or non-linear dynamics model of an engine and to identify the working conditions by the fluctuation of transient rotation speed of the engine's principal shaft[8-10]. Compared to the approaches listed

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above, the vibration signal of cylinder-head is very easy to measure, and the whole progress in measurement has no effect on the working of the engine. So this kind of method shows its obvious advantages in the large number of repeatable and non-damaging experiments, which is imperative for the design of cylinder shape and the configuration of a calibration program.

However, the vibration signal of the cylinder-head, which includes a large amount of wideband-frequency jamming signals, is very complicated[11, 12]. As a result, the interior information, which is useful for misfiring detection, is relatively difficult to distill from the original signal. While wavelet analysis is a signal process approach which can decompose the signal with multi-scale wavelet function and eliminate the strong noise from the original signal. And it is widely used in the processing of complicated signals. Therefore, it is significant and practicable, for the detection of engine misfiring, to introduce wavelet analysis into the analysis of cylinder-head vibration signals.

2 Principle of wavelet transformation

2.1 Continuous wavelet transformation

If the function $\psi(x)$ in function space $L^2(R)$ meets the equation below:

$$C_\psi = \int_{R^*} \frac{|\psi(\omega)|^2}{|\omega|} \mathrm{d}\omega < \infty \qquad (1)$$

The function $\psi(x)$ can be a mother wavelet function. The continuous wavelet transformation of arbitrary function or signal $f(x)$ is defined as below:

$$W_f(a,b) = \frac{1}{\sqrt{|a|}} \int_R f(x) \overline{\psi}\left(\frac{x-b}{a}\right) \mathrm{d}x \qquad (2)$$

Where $\overline{\psi}\left(\frac{x-b}{a}\right)$ is the Fourier transformation of $\psi\left(\frac{x-b}{a}\right)$ in equation (2), a is the scale gene of $\psi(x)$, and b is the translation gene of $\psi(x)$.

2.2 Discrete wavelet transformation

Although continuous wavelet transformation is still used in feature extraction, transforming the signal with every possible scale and translation results in a large amount of data. If the signal can be transformed in a limited discrete scale and discrete translation where the useful information is kept, then the effort required for wavelet transformation is greatly reduced. Thus, discrete wavelet transformation is wildly used instead of continuous wavelet transformation.

The dyadic discrete result of scale gene in equation (2) is $a_k = 2^{-k}$, and the dyadic discrete of translation gene is $b_k = 2^{-k}j$. Therefore, the dyadic discrete wavelet transformation of $f(x)$ is:

$$W_f^k(x, j) = \int_R f(x) \overline{\psi_{(2^{-k}, 2^{-k}j)}}(x) \mathrm{d}x \qquad (3)$$

One of the most important characteristics of discrete wavelet transformation is its function of filtering the original signal. The original signal can be decomposed into low-frequency approximate component and high-frequency approximate component after discrete wavelet transformation. And the relation of 3-level multi-resolution decomposition at original signal S is noted as $S=A_3+D_3+D_2+D_1$. Figure 1 shows the structure tree of 3-level multi-resolution decomposition.

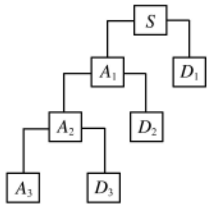


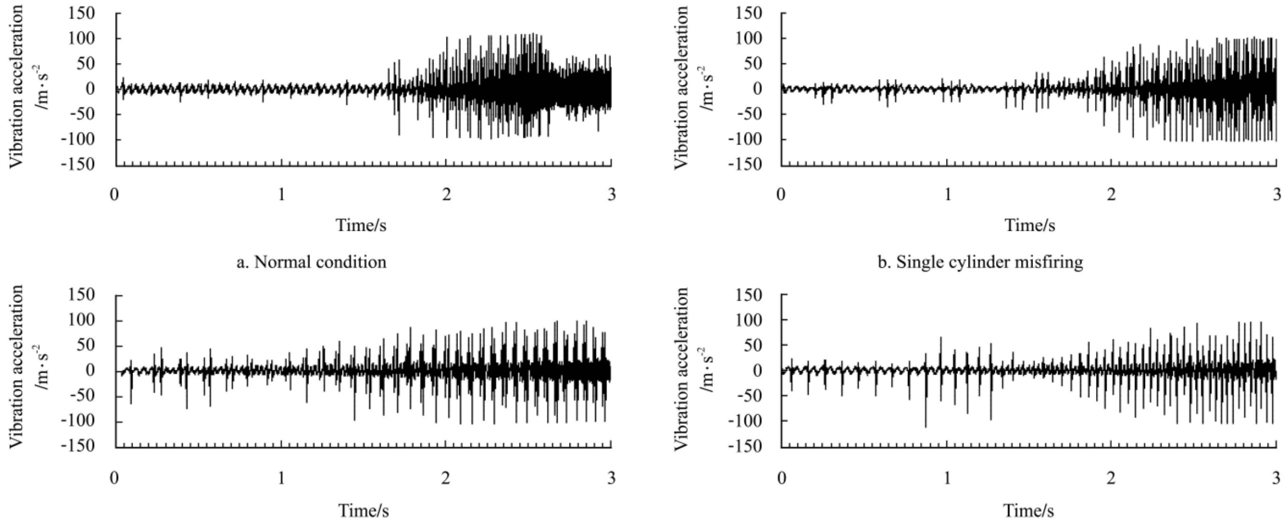
Fig.1 Structure tree of the 3-level decomposition

According to figure 1, the component A is the low-frequency component decomposed with large scale gene, and component D is the low-frequency component decomposed with small scale gene. If the frequency bandwidth of original signal S is [0, f], the components after decomposition are A_3[0,f/8], D_3[f/8,f/4], D_2[f/4,f/2], D_1[f/2,f] in the end.

The commonly used wavelet functions include Daubechies wavelet, Morlet wavelet, B-Spline wavelet and so on. Moreover, Daubechies wavelet is especially widely used because of its symmetrical, continuous, compacted and orthogonal characteristics[13, 14].

3 Data acquisition of engine cylinder-head vibration signal

The engine studied in experiment was an in-line four-cylinder diesel engine, whose combustion sequence of cylinders was 1-3-4-2. The piezoelectricity accelerometer was disposed on the top of the cylinder-head so as to detect the vibration signal. Thereafter, the vibration accelerating signal detected by accelerometer was amplified and filtered with an electric charge amplifier, and was then sampled by the data acquisition system built with LabVIEW. The sampling frequency was 4096 Hz. Single cylinder misfiring, double cylinders continuous misfiring and double cylinders alternate misfiring faults were designed by cutting diesel oil route artificially. And the data acquisition system sampled the vibration acceleration signal for 3 seconds while engine was rapidly accelerating to a high speed and kept running at the high speed after a certain period of running at idle speed.



a. Normal condition b. Single cylinder misfiring

c. Double cylinders continuous misfiring d. Double cylinders alternate misfiring

Fig.2 Vibration acceleration signals of four conditions

4 Experimental results and analysis

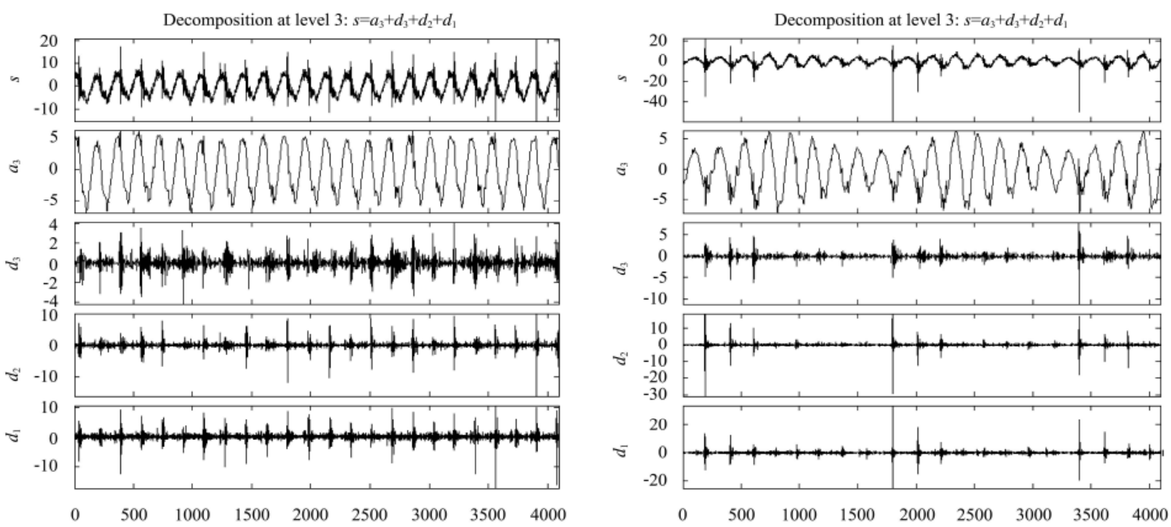
4.1 Experimental results

The vibration signals detected under normal condition, single cylinders misfiring condition, double cylinders continuous misfiring condition and double cylinders alternate misfiring condition while engine was rapidly accelerating from idle speed to high speed are showed in Figure 2.

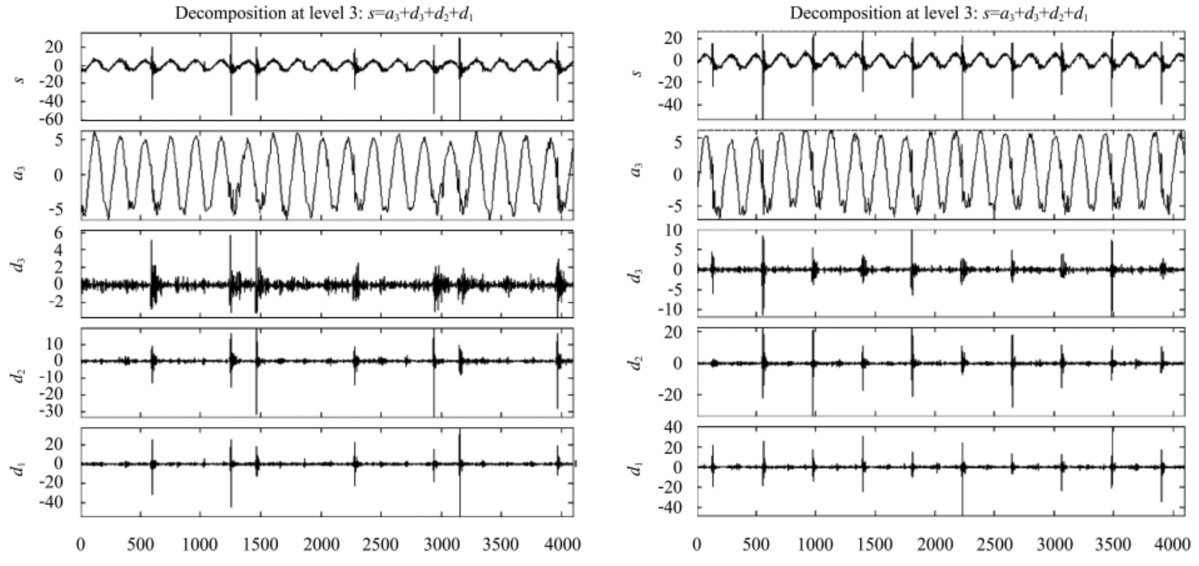
4.2 Wavelet analysis of cylinder-head vibration signal

Figure 2 shows that the original cylinder head vibration signals based on four conditions include not only low-frequency periodic signal, but also complicated high-frequency signal. Thus, it was difficult to distinguish misfiring defaults from the original signals directly, especially in high-speed segment. And the experiment demonstrates that misfiring defaults can be clearly distinguished after 3-level decomposition of the original signals with db3 wavelet.

The results shown in figure 3, 4 and 5 are the wavelet decompositions of vibration signals when the engine is running at idle speed, accelerating speed and high speed under the four conditions of normal and fault. The signal S represented the original signal. Moreover, d_1, d_2 and d_3 were respectively the first, second and third level high-frequency signals decomposed by wavelet. And a_3 was the low-frequency vibration signal of 3-level decomposition. According to the principle of discrete wavelet transformation, bandwidth of a_3 covers from 0 Hz to 256 Hz. Bandwidth of d_1 covers from 256 Hz to 512 Hz. Bandwidth of d_2 covers from 512 Hz to 1024 Hz. Bandwidth of d_3 covers from 1024 Hz to 2048 Hz.



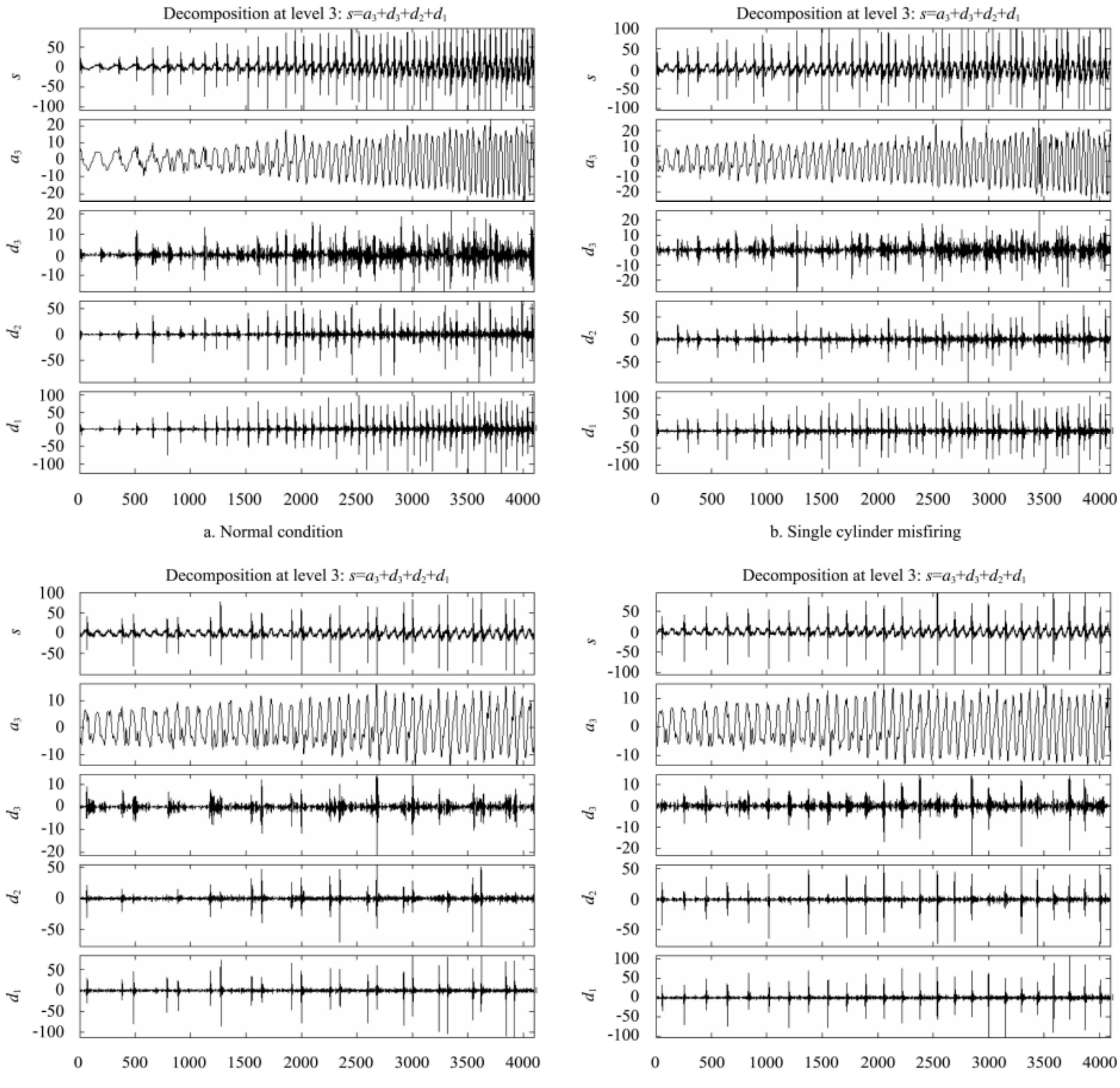
a. Normal condition b. Single cylinder misfiring



c. Double cylinders continuous misfiring

d. Double cylinders alternate misfiring

Fig.3 Wavelet decomposition of vibration signals under four conditions in idle section



a. Normal condition

b. Single cylinder misfiring

c. Double cylinders continuous misfiring

d. Double cylinders alternate misfiring

Fig.4 Wavelet decomposition of vibration signals under four conditions in accelerate section

Figure 3 shows the wavelet decomposition results of vibration signal in idle-speed segment under the four conditions. The results demonstrated that the low-frequency signal presented the periodic fluctuation when engine ran under the normal condition and each wave crest of high-frequency signal was certainly corresponding to one wave crest of low-frequency signal. The low-frequency vibration signals of misfiring faults were essentially the same as those of normal condition, but high-frequency signals of faults were obviously different from those of normal condition. Compared between the wave crest of low-frequency signal and the wave crest of high-frequency signal showed that one wave crest disappeared after every three high-frequency wave crest when single cylinder misfires, two wave crests disappeared after every two high-frequency wave crests when double cylinders continuous misfire, and one wave crest disappeared after every one high-frequency wave crest when double cylinders alternately misfire.

Figure 4 shows the wavelet decomposition results of vibration signal in accelerating segment under the four conditions. The results demonstrated that the amplitude and frequency of low-frequency vibration signals were growing as the accelerating of the engine continued. But the corresponding relation of accelerating segment between high-frequency wave crest and low-frequency wave crest were certainly the same as those in idle segment.

Figure 5 shows the wavelet decomposition results of vibration signal in high speed segment under the four conditions. The results demonstrated that the corresponding relation of wave crests between high-frequency signal and low-frequency signal were also the same as those in idle segment and accelerating segment.

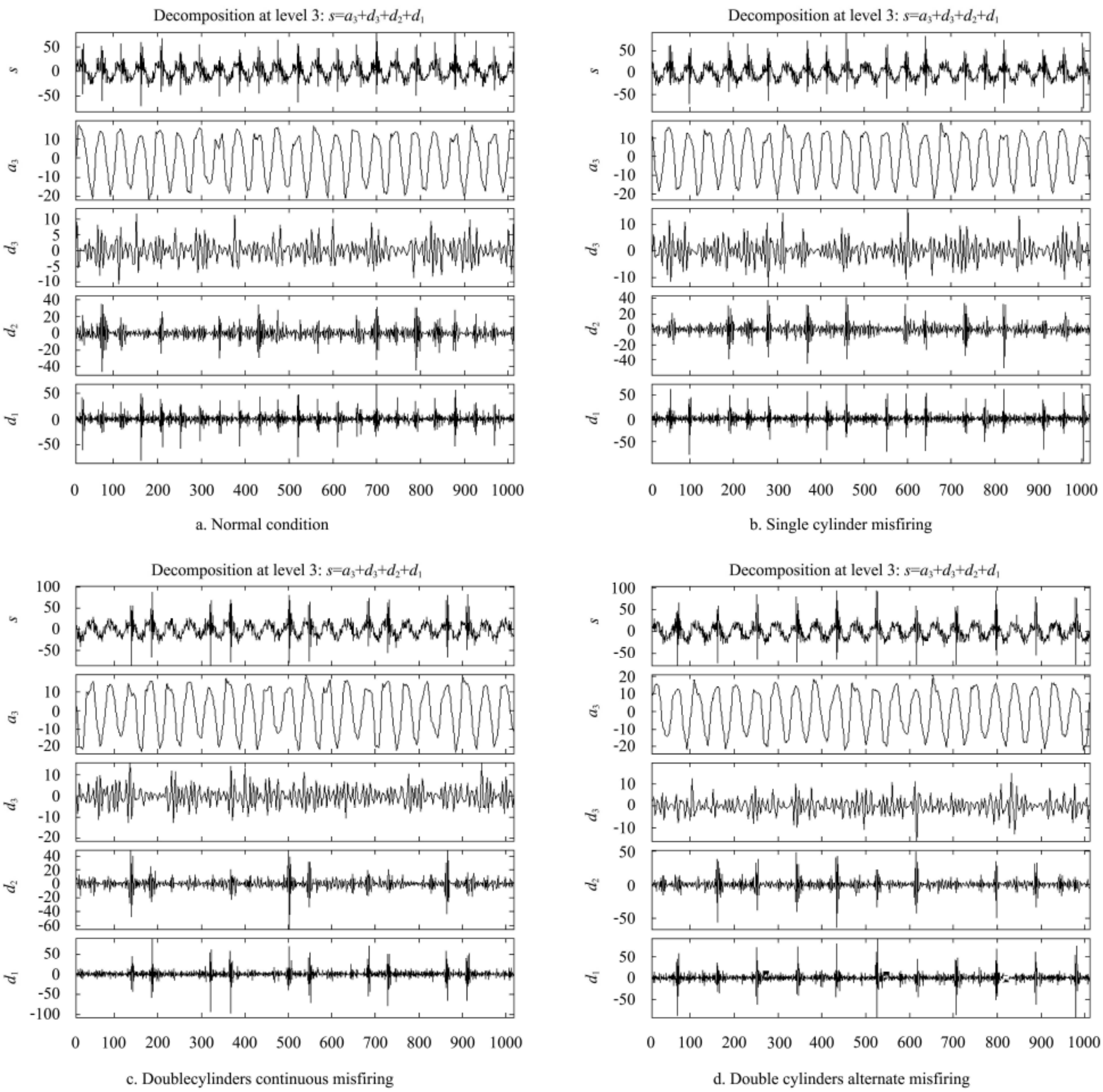


Fig.5 Wavelet decomposition of vibration signals under four conditions in high speed section

The results above imply that the low-frequency vibration of cylinder head is caused by the rotation of the principal shaft. This is why the fluctuation frequency of low-frequency signal grows with the increasing rotation speed of the principal shaft and why the fluctuation frequency of the low-frequency signal doesn't change when the cylinder misfired, while the principal shaft kept rotating at a certain speed.

The results also imply that the high-frequency vibration of the cylinder head is caused by the combustion of cylinders, and the high-frequency wave crest disappears when the engine misfires. That is why a wave crest of high-frequency signal disappear after alternating every third wave crest when the signal cylinder misfired, two wave crests of high-frequency signal disappeared after alternating every two wave crests when double cylinders continuously misfired and one wave crest of high-frequency signal disappeared after alternating every wave crest when double cylinders alternately misfired.

Thus, the misfiring faults can be detected by comparing the wave crest of the high-frequency signal with wave crest of the low-frequency signal. The diagnostic results of accelerating segment and high speed segment are more obvious than that of idle speed segment. The reason is that the rotation speed of the idle segment, whose high-frequency vibration was comparatively feebler than that of high speed segment, was lower than the rotation speed of the high speed segment, and the accelerating segment is essentially a non-stable case, whose vibration was more intensive than that of a stable case.

In the end, what needs to be pointed out in this experiment is that further research on the combustion principles of engines, and that the choice of appropriate wavelet function to process the original signal can increase the accuracy of misfiring faults detection.

5 Conclusions

1) The low-frequency vibration of an engine cylinder-head is related to the rotation of the principal shaft, and the high-frequency vibration is related to the combustion in the cylinder. There is certainly a corresponding relationship between high-frequency wave crest and low-frequency wave crest under the four conditions of normal and faults at idle segment, accelerating segment and high speed segment.

2) The misfiring fault and the types could be detected by analyzing the corresponding relationship between the wave crest of high-frequency vibration signal and the wave crest of low-frequency vibration signals.

3) Detection on the misfiring fault with wavelet is effective and feasible. Decomposing the vibration signal of engine cylinder-head by wavelet could clearly educe the corresponding relationship between high-frequency and low-frequency signals.

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