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Fault Diagnosis of Diesel Engine Misfire Based on Frequency Domain Feature and Neural Network

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Abstract: In order to gain a deeper understanding of the mechanism of diesel engine misfire faults and effectively improve the diagnostic accuracy of misfire faults, a diesel engine misfire fault diagnosis method based on frequency domain features and neural networks is proposed based on diesel engine speed signals and cylinder pressure vibration signals. For three types of faults: complete misfire of a single cylinder, complete misfire of two cylinders, and certain degree of misfire of a single cylinder, the influence of low harmonic excitation torque vector on the speed signal was obtained through frequency domain analysis of the speed signal. A polar coordinate graph was proposed to display the fault characteristics under different misfire modes, and a three-level diagnostic network based on fully connected neural network was designed to achieve fault diagnosis. Applying this method to a certain type of diesel engine, the results show that it can accurately extract misfire fault information and effectively diagnose misfire faults.

Keywords: diesel engine; fire malfunction; frequency domain analysis; neural network

1. INTRODUCTION

The engine is the core power system of a car, and its performance directly determines the working condition of the car. The working process of diesel engines is very complex, with variable combustion and easy occurrence of misfire faults. Diesel engine misfire can lead to reduced combustion efficiency, increased vibration, decreased output torque, and even deformation or fatigue damage of the crankshaft.

In the process of fire fault diagnosis, feature extraction and pattern recognition are two important steps. Jia Jide et al. proposed a diesel engine misfire fault diagnosis method based on wavelet and deep belief network, which improved the accuracy of misfire fault diagnosis. Liu Xin et al. proposed a two-dimensional fault feature extraction model based on grayscale image texture analysis to address the problems of difficult parameter acquisition and poor accuracy caused by noise pollution in traditional diagnostic methods. This model can effectively reduce noise pollution and simplify the calculation process.

Zhao Liang et al. proposed the GA-BP neural network algorithm to improve the accuracy of neural networks in engine misfire fault diagnosis. Not only does it shorten the training time, but it also greatly improves the accuracy of fault diagnosis. Wang Dongsheng and others designed a diesel engine fault diagnosis and recognition system based on BP neural network, which takes the frequency and energy characteristics of diesel engine vibration signals as the characteristic values of vibration signals, and the recognition accuracy has been significantly improved. Hu Jie et al. proposed a misfire fault diagnosis algorithm based on the instantaneous angular acceleration of the crankshaft, which can diagnose misfire faults but fails to effectively distinguish fault modes. This algorithm utilizes work time and BP neural network to effectively identify different misfire fault modes and locate misfire cylinders.

In order to further improve the accuracy of diesel engine misfire fault diagnosis, this paper uses frequency domain analysis and neural network methods based on diesel engine speed signals to study single cylinder misfire, two cylinder misfire, and transient state misfire faults of diesel engines.

2. FEATURE EXTRACTION OF FIRE FAULTS BASED ON FREQUENCY DOMAIN ANALYSIS

For a four stroke diesel engine, the tangential torque generated by the force acting on the single cylinder crankshaft is as follows:

$$M_g = M_{g0} + \sum_{v=0.5}^{\infty} M_{gv} \sin(v\omega t + \varphi_v) \quad (1)$$

$$M_j = m_j R^2 \omega^2 \left(\frac{\lambda}{4} \sin \omega t - \frac{1}{2} \sin 2\omega t - \frac{3\lambda}{4} \sin 3\omega t - \frac{\lambda^2}{4} \sin 4\omega t + \frac{5\lambda^3}{32} \sin 5\omega t \right) \quad (2)$$

The harmonic frequency v of the tangential force generated by the gas excitation force on the crankshaft is calculated from the 0.5 order. This is because for a four stroke engine, the work cycle of each cylinder is two engine revolutions, and the basic variation period of the gas excitation force is the time it takes for the engine to rotate two revolutions. Therefore, its basic frequency is ω/2. For ease of expression, 1/2 is multiplied into the order.

Based on the above analysis, the excitation torque vectors of each harmonic of the six cylinder four stroke engine are shown in Figure 1.

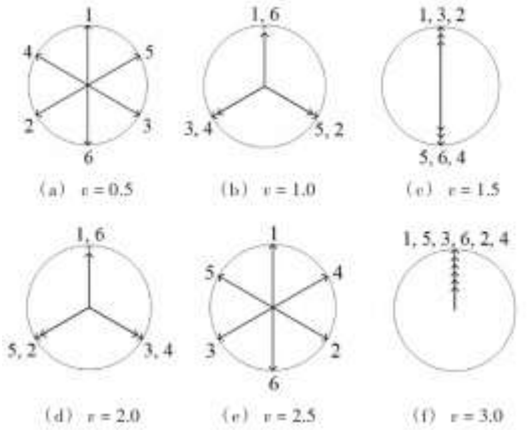

Figure.1 Excitation torque vector for each harmonic (<3) of a six cylinder four stroke engine

In the analysis of shaft vibration signals, using harmonics (also known as order or ratio) to express the ratio of vibration frequency to shaft frequency (rotation frequency of the shaft), and using harmonics as the horizontal axis, will be beneficial for comparing and analyzing the fluctuation patterns of speed signals at different speeds.

3. NEURAL NETWORK DIAGNOSIS METHOD BASED ON FREQUENCY DOMAIN FEATURES

Mainly utilizing amplitude information of 0.5-2.5 harmonics and phase information of 0.5 harmonics combined with neural network methods for diagnosis. The overall structure adopts a 3-layer judgment mode, as shown in Table 1.

Table 1. Overall Structure of Diagnostic Algorithm

	Intake valve clearance(mm)	Exhaust valve clearance(mm)	Working condition
The 1st Judgment	ANN-1	Determine Misfire Mode	0.5-2.5 Harmonic Amplitudes
The 2nd Judgment	ANN-2	Locate Misfire Cylinder	0.5 and 1 Harmonic Phases
The 3rd Judgment	ANN-3	Determine Single Cylinder Misfire Degree	0.5-2.5 Harmonic Amplitudes

Due to the confusion of phase information in normal operating conditions and some misfire conditions, ANN-1 only uses amplitude as the fault feature. In specific implementation, the amplitude of 0.5~2.5 harmonics is compared to 3 harmonics, and the data is normalized before being used as input data. The ANN-2 part uses 0.5 harmonic phase information to locate single cylinder misfire, continuous two cylinder misfire, and two cylinder misfire with an interval of one cylinder. It uses 1 harmonic phase to locate two cylinder misfire faults with an interval of two cylinders. The ANN-3 section will use the same fault characteristics as the first section to evaluate the degree of single cylinder misfire.

4. FIRE FAILURE ANALYSIS

By analyzing the experimental results, partial patterns of changes in speed amplitude and phase caused by misfire can be obtained. In order to better represent the characteristics of amplitude and phase, a polar coordinate graph was used. Figure 2 shows the frequency domain analysis results (0.5-3 harmonics) of the engine under normal and single cylinder misfire conditions under no-load conditions.

The results indicate that in terms of amplitude, compared to normal operating conditions, the first five harmonic amplitudes increase when the misfire fault is a single cylinder. In terms of phase, the main harmonic phases of normal and fault conditions are consistent, both falling within the range of 180 °± 30 °, which satisfies the law of consistent excitation force phases for the six cylinders in Figure 3 (f); Although the phase interval consistency of other harmonics has decreased, there is still a certain degree of similarity, for example, the number of phases under each harmonic conforms to the theoretical results, and the phase changes still follow the ignition order; In some harmonics, the data points of the operating conditions are not concentrated at the center of the graph, such as the 2nd harmonic in the graph, which shows an overall offset. It can be seen that this is not caused by a misfire fault, but may be due to internal factors such as inertia force in the engine. The rules mentioned here can all serve as fault characteristics for fault diagnosis.

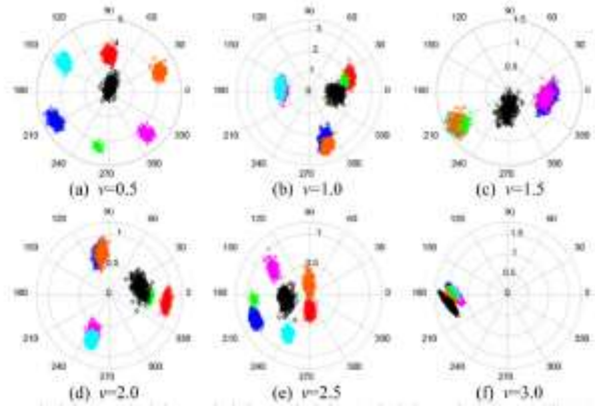

Figure.2 Frequency domain analysis results of engine under normal and single cylinder misfire conditions under no-load conditions

For the convenience of analysis, the misfire fault modes of two cylinders are classified into three categories based on the similarity of their misfire characteristics. That is, in terms of ignition order: continuous misfire of two cylinders, misfire of two cylinders separated by one cylinder, and misfire of two cylinders separated by two cylinders. As shown in Figure 3, misfire of cylinders 1 #5 #, 4 # 5 #, and 1 # 6 # is one of these three modes.

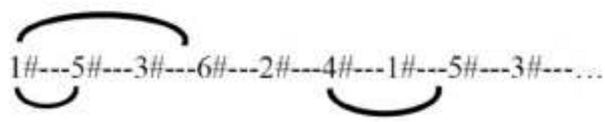

Figure.3 Two cylinder misfire mode

The frequency domain analysis results of the engine under normal and two cylinder misfire conditions under no-load conditions are shown in Figure 6, which includes all types of two cylinder misfire. When two consecutive cylinders misfire, as indicated by the blue markings in the figure, the equilibrium states of 0.5, 1, 2, and 2.5 harmonics will be disrupted, but the impact on 1.5 and 3 harmonics will be minimal; When a misfire occurs between two cylinders separated by one cylinder, the equilibrium states of 0.5, 1, 1.5, 2, and 2.5 harmonics will be disrupted, with only 3 harmonics being minimally affected, as indicated by the red markings in the reference diagram. However, the amplitude variation here exhibits different patterns from the continuous two cylinder misfire condition at different harmonics. For example, at 0.5 harmonics, due to the larger synthesized amplitude of the excitation force vector during continuous two cylinder misfire (60 ° angle for continuous two cylinders and 120 ° angle for two cylinders separated by one cylinder), the fluctuation amplitude of the 0.5 harmonic speed during continuous two cylinder misfire is larger; At the first harmonic, the phase angles of misfires in two consecutive cylinders and two cylinders with an interval of one cylinder are 120 ° and 240 °, respectively, causing the same amplitude change; When the two cylinders separated by two cylinders misfire, the magenta markings in the reference diagram indicate that the balance state of harmonics 1 and 2 is disrupted, while harmonics 0.5, 1.5, 2.5, and 3 are minimally affected. Due to the phase relationship of the excitation force of the misfiring cylinder, the amplitude changes of the 1st and 2nd harmonics caused by this misfiring condition are significantly greater than those of the first two misfiring states, and also greater than those of the single cylinder misfiring condition.

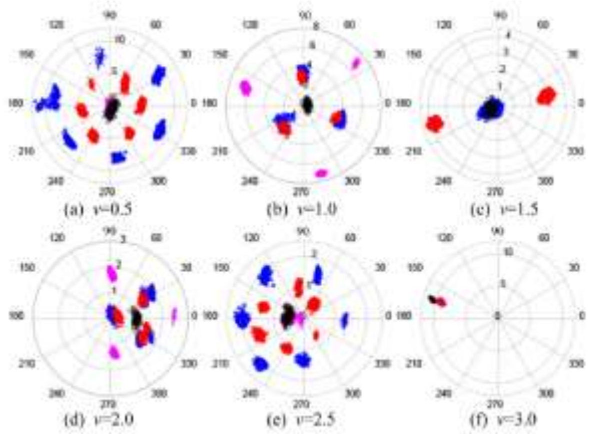

Figure.4 Different harmonic amplitudes and phases of rotational speed under no-load conditions

In terms of the amplitude fluctuations of different harmonics of the speed, the amplitude changes of two cylinder misfire in different modes are significantly different at 0.5-2.5 harmonics. Therefore, the misfire fault of two cylinders can be determined by the amplitude changes of each harmonic. From the phase information, there are still some highly fluctuating phase distributions, such as the first 5 harmonics of normal operating conditions, the 0.5 and 2.5 harmonics of misfires between two cylinders, etc. This is mainly because the crankshaft is in a balanced state under these harmonics. For harmonics with significantly increased amplitude, the phase information is clearer, such as the 0.5 harmonic of consecutive two cylinder misfires. Secondly, under light load conditions, the distribution of a certain fault under some harmonics is more dispersed, which may be due to the relatively small gas excitation force. In addition, as the speed increases, at harmonics 1, 1.5, 2, and 2.5, each fault undergoes a movement similar to cylinder misfire in the overall position shown in the figure, which appears to be the influence of some kind of interference force gradually strengthening. Analysis suggests that it is the influence of inertia force. To distinguish these fault modes, it is necessary to integrate these features by fitting unknown underlying patterns. We will use neural networks, a method based on data and statistical patterns, for processing.

The results show that in terms of amplitude, when two cylinders misfire, the equilibrium state of 0.5-2.5 harmonics will change, and the amplitude changes at 0.5 and 1 harmonics are still greater, and the regularity is more obvious; In terms of phase, 0.5 harmonics can be used for two consecutive cylinder misfires and two cylinder misfires with an interval of one cylinder.

4. CONCLUSION

This article is based on the speed signal and cylinder pressure vibration signal of a diesel engine. Through frequency domain analysis of the speed signal, the influence law of the low harmonic excitation torque vector on the speed signal is obtained. A polar coordinate graph is proposed to display the fault characteristics under different misfire modes, achieving misfire fault diagnosis. A three-level diagnostic network based on fully connected neural networks was designed for three types of faults: complete misfire of a single cylinder, complete misfire of two cylinders, and partial misfire of a single cylinder. The verification results show that the fault diagnosis model can fully recognize fault data, and the work in this paper can provide some reference for the design of diesel engine misfire fault diagnosis.

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