

Review of Automobile Engine Fault Diagnosis Technologies: From Traditional Methods to AI-based Intelligent Systems

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Abstract

As the core power component of vehicle, the accuracy and efficiency of fault diagnosis of automobile engine are directly related to driving safety, economy and environmental protection. With the rapid development of the automobile industry, the engine structure is becoming more and more complex, and the degree of electronic control is increasing. The traditional diagnosis method based on manual experience has been difficult to meet the needs of modern maintenance. Based on a comprehensive review of representative studies sourced from the China National Knowledge Infrastructure (CNKI) database over the recent five years, this paper systematically reviews the evolution of automobile engine fault diagnosis technologies-from traditional manual approaches to AI-based intelligent systems. Firstly, the article reviews the traditional diagnostic methods that rely on manual experience and basic instruments, and analyzes their limitations. Secondly, it focuses on the modern detection technology based on vibration, sound, temperature and other signals, as well as the application of on-board diagnostic system (OBD). Then, the core algorithms and models of artificial intelligence technology represented by machine learning and deep learning in engine intelligent diagnosis are deeply analyzed, such as BP neural network, 1D-CNN, ELM, etc., and their performance advantages are compared through cases. Finally, the future trend of remote intelligent diagnosis and predictive maintenance integrating Internet of Things, big data and cloud computing is prospected. The research shows that the paradigm shift from " experience-driven " to " data-intelligent-driven " is the key path to improve the level of engine fault diagnosis. Multi-technology integration and real-time remote monitoring will become the main direction of future development.

Keywords

Automobile Engine; Fault Diagnosis; Deep Learning; Signal Processing; Intelligent Diagnosis System.

1. Introduction

The automobile engine is a complex system integrating mechanical, electronic and thermal power. There are many types of common faults, including difficulty in starting, unstable idle speed, lack of power, abnormal noise and high temperature[1]. The causes of these faults are complex, which may involve the synergistic failure of ignition system, fuel system, intake and exhaust system, electronic control system and mechanical structure[2]. The traditional automobile maintenance mode is highly dependent on the personal experience and sensory judgment of the maintenance technician (such as " listening to the sound and distinguishing the cause "), and has inherent defects such as strong subjectivity, low efficiency, and difficulty in reproducing intermittent faults[3,4]. With the wide

application of electronic control unit (ECU) and various sensors, although the self-diagnosis ability of vehicles has been improved, the on-board diagnostic system (OBD) is mainly oriented to emission-related components, and its functions are still relatively limited[5]. Therefore, exploring efficient, accurate and intelligent engine fault diagnosis technology has become an important research topic in the field of automobile maintenance.

In recent years, the rapid development of signal processing technology, artificial intelligence algorithm and Internet of things communication technology has injected new vitality into engine fault diagnosis. Many scholars have conducted in-depth research from different technical routes. This paper aims to systematically review and comment on these research results, analyze the characteristics and application scenarios of various technologies, and look forward to the future development direction, in order to provide reference for follow-up research and industry application.

2. Traditional Fault Diagnosis Methods and Their Limitations

Before the popularization of intelligent technology, engine fault diagnosis mainly depends on two ways : one is the technician 's experience judgment method, that is, by observing the exhaust color, touching the temperature, listening to the abnormal sound and other ways to initially locate the fault[6]; the second is the basic instrument detection method, such as using a multimeter to measure the circuit on and off, using a pressure gauge to detect cylinder pressure and fuel pressure, and using a vacuum gauge to check the sealing of the intake system[7]. In his case study, Li Lan systematically summarized the diagnosis process of start-up system, fuel system and cooling system, and emphasized the diagnosis idea of " from the outside to the inside, from simple to complex "[1]. Based on the principle of electronic control, Lou Xiaohui drew the fault analysis mind map of engine start-up difficulty and poor operation in detail, highlighting the systematic investigation of the three elements of ignition, fuel injection and compression[8].

Although these methods are still valuable in simple fault handling, their limitations are increasingly prominent. First of all, the diagnostic accuracy is highly dependent on the level of technicians, and the difference in experience of different personnel may lead to completely different conclusions[3]. Secondly, for accidental, compound or early minor faults, manual means are difficult to effectively capture[9]. Finally, in the face of increasingly complex electronic control systems, it is difficult to analyze the sensor data flow and waveform signals in depth by experience alone, and the diagnosis efficiency is low[10]. Therefore, it is imperative to introduce more objective and quantitative modern technical means.

3. Diagnosis Method based on Signal Processing and Modern Detection Technology

In order to overcome the shortcomings of manual diagnosis, researchers have turned their attention to the quantitative analysis of various physical signals generated during engine operation.

3.1 Vibration and Sound Signal Analysis

Vibration and sound signals contain rich engine state information. The experimental study of Wang Yanli et al.shows that the vibration sensor installed on the engine cylinder can effectively capture the high-frequency vibration enhancement caused by the wear of the crankshaft bearing and the periodic low-frequency jitter caused by the abnormal valve[9]. Du et al.used one-dimensional convolutional neural network (1D-CNN) to directly process the original vibration signal, and achieved high-precision classification of different valve clearances and camshaft looseness faults without relying on artificial feature extraction, with an accuracy rate of more than 98 %[11]. In terms of sound analysis, Akbalik et al.compared the effect of Mel Frequency Cepstrum Coefficient (MFCC) and Discrete Wavelet Transform (DWT) combined with Extreme Learning Machine (ELM). It was found that the average diagnostic accuracy of MFCC + ELM combination for various faults (such as spark plug problem, abnormal airflow, etc.) in real vehicle environment reached 92.14 %, which was better than DWT feature[12]. In addition, the AMPNet system developed by Federishin et al.integrated engine

sound, vibration accelerometer data, and vehicle metadata. After the deployment of the actual auction platform, the engine-related arbitration claims were reduced by 20.85 %, demonstrating the great potential of multi-modal sound and vibration analysis in industrial-scale applications.[13]

3.2 Temperature and Non-contact Detection

Temperature is an important index to reflect the combustion state of the engine. Ou Weixin and others pioneered the application of infrared temperature sensor to the fault diagnosis of missing cylinder. By comparing the temperature difference of each cylinder at the exhaust manifold, the cylinder that does not work can be quickly located. Experiments show that the method is accurate in diagnosis, and does not require contact with high-temperature components, and is simple and safe to operate[14]. Infrared thermal imaging technology can also be used to detect problems such as cooling system blockage and poor heat dissipation[7]. These non-contact temperature measurement methods provide efficient tools for rapid screening of thermal-related faults.

3.3 On-board Diagnostic System (OBD) and Data Flow Analysis

The OBD-II system is the standard configuration of modern automobiles. Peng Liang elaborated on the working principle of reading the standardized fault code (DTC) and real-time data stream by connecting the ECU. [7]A case study of 2018 Toyota Corolla shows that although the fault code P0300 (misfire diagnosis) can indicate the direction of the problem, it still needs to be combined with data flow analysis (such as abnormal air flow sensor) and waveform analysis to accurately locate.[15]. OBD technology realizes the initial electronization and standardization of the diagnosis process, but its diagnosis depth is limited by the preset algorithm and threshold of ECU, and its ability to predict the progressive failure of mechanical components is insufficient[5].

4. Intelligent Fault Diagnosis Technology based on Artificial Intelligence

With the improvement of big data and computing power, artificial intelligence (AI) has become the core driving force to promote the leap of fault diagnosis technology from " electronic " to " intelligent."

4.1 Traditional Machine Learning Model

Support vector machine (SVM) and artificial neural network (ANN) are the earliest AI models applied to fault diagnosis. Xu Jianqiang and others proposed to combine chaotic neural network with expert system to deal with atypical and difficult faults caused by various complex factors. By combining exhaust gas analysis data, the system shows the learning speed and diagnostic accuracy beyond the traditional BP neural network[2]. The crankshaft speed fluctuation method mentioned by Huang Jinhui in the review is essentially using the instantaneous speed signal as input, which can be combined with SVM and other classifiers for misfire fault identification[16]. However, the feature extraction ability of these shallow models is limited, and the performance depends largely on the quality of manual feature design.

4.2 Deep Learning Model

The emergence of deep learning solves the bottleneck that traditional models are difficult to automatically extract deep features. In his study, Du et al.systematically compared the effects of 1D-CNN with CV-SVM, PSO-PNN and BP neural network. When dealing with the original vibration signal, the diagnostic accuracy of the 1D-CNN model is as high as 99.88 %, far exceeding the 55 % of the BP neural network and 97.5 % of the CV-SVM, and the diagnostic time is shorter (0.2 seconds), which fully reflects the great advantage of end-to-end learning in mining the deep features of the original signal[11]. Yang et al.introduced the application prospect of convolutional neural network (CNN) in processing vibration and acoustic image, and recurrent neural network (RNN) in analyzing time series data (such as speed and oil pressure), and pointed out that RNN has unique value in predicting fault development trend[17]. In addition, the generative adversarial network

(GAN) is also used to generate high-quality fault samples to solve the problem of scarcity of actual fault data.[17]

5. Remote Diagnosis and Predictive Maintenance System

Under the background of digitalization, the evolution of diagnostic technology has broken through the category of local analysis of bicycles and developed towards systematization and networking.

Qin Jiancan et al. designed a remote fault setting system for ignition coil circuit of automobile engine based on Internet of Things (IoT). The system integrates data acquisition (high-precision sensors), communication (4G / 5G / NB-IoT), cloud processing (big data analysis and fault model construction) and remote control modules. Maintenance personnel can remotely monitor the circuit status, inject simulated faults and diagnose them through the user terminal, which greatly improves the efficiency and convenience of teaching and remote maintenance[18]. Song Mingxiang further discussed the application of remote monitoring in predictive maintenance. Through the cloud platform to gather massive vehicle operation data, the machine learning algorithm is used to construct a fault prediction model, which can identify early fault symptoms, and formulate personalized maintenance strategies according to individual differences of vehicles (such as driving conditions and driving habits), so as to realize the transformation from " corrective maintenance " to " condition-based maintenance "[5]. This system represents an important direction for the operation and maintenance of smart cars in the future.

6. Conclusion

In general, the fault diagnosis technology of automobile engine is undergoing a profound change from ' relying on experience ' to ' relying on computer brain intelligent analysis '. In the past, car repair mainly relied on the experience of technicians and basic tools such as multimeter. This method is not only inefficient, but also difficult to deal with those occasional or complex electronic system failures. Now, with the popularity of sensors and OBD systems, diagnosis has become electronic and standardized, but there is still a distance from true ' intelligence '. Nowadays, the addition of artificial intelligence is the biggest bright spot. The study found that deep learning models such as 1D-CNN can automatically ' learn ' fault features directly from the original signals such as engine vibration and sound. Not only is the accuracy extremely high (some experiments can reach more than 99 %), but also the speed is fast. This is much more powerful than traditional machine learning methods that rely on manual analysis of data and extraction of features in the past. At the same time, the combination of sound, vibration, temperature and other information can also make the diagnosis results more reliable and will not be biased. The future trend is to make diagnostic systems more ' smart ' and ' networked '. Through the Internet of Things and cloud platform, vehicles can transmit real-time data to the background for remote monitoring and predictive maintenance. This not only means that the fault can be warned before it occurs, but also can customize the exclusive maintenance plan according to the actual use of each vehicle, and finally realize the transformation from ' broken repair ' to ' early prevention '.

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