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Improved automated diagnosis of misfire in internal combustion engines based on simulation models

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ABSTRACT

In this paper, a new advance in the application of Artificial Neural Networks (ANNs) to the automated diagnosis of misfires in Internal Combustion engines(IC engines) is detailed. The automated diagnostic system comprises three stages: fault detection, fault localization and fault severity identification. Particularly, in the severity identification stage, separate Multi-Layer Perceptron networks (MLPs) with saturating linear transfer functions were designed for individual speed conditions, so they could achieve finer classification. In order to obtain sufficient data for the network training, numerical simulation was used to simulate different ranges of misfires in the engine. The simulation models need to be updated and evaluated using experimental data, so a series of experiments were first carried out on the engine test rig to capture the vibration signals for both normal condition and with a range of misfires. Two methods were used for the misfire diagnosis: one is based on the torsional vibration signals of the crankshaft and the other on the angular acceleration signals (rotational motion) of the engine block. Following the signal processing of the experimental and simulation signals, the best features were selected as the inputs to ANN networks. The ANN systems were trained using only the simulated data and tested using real experimental cases, indicating that the simulation model can be used for a wider range of faults for which it can still be considered valid. The final results have shown that the diagnostic system based on simulation can efficiently diagnose misfire, including location and severity.

1. Introduction

Misfire is a very common combustion fault for IC engines and many works have been put forward to study vibration-signal-based misfire diagnosis. The vibration based misfire diagnosis can be further divided into two types: one is based on the translational acceleration signals measured on the engine block, while the other is based on the torsional vibration signal of the crankshaft. The acceleration signals contain more information about high frequency components while the torsional vibration can give more precise information about low frequency components. Some research [1–7] has looked at using translational acceleration signal measurement for the misfire diagnosis. This approach involves recording vibrations at a position either on the engine block or on the cylinder head and requires the design of an appropriate inverse filter, usually

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in the form of a parametric model. In contrast, more research [8–19] has been done on misfire diagnosis based on the crankshaft angular vibration signal. For small engines with nearly rigid crankshafts, it can be considered that there is a linear relationship between the chamber pressure and torsional vibration, and using torsional vibration for the misfire diagnosis should be reliable under this condition. But for the bigger engines with long and flexible crankshafts, the combustion in different cylinders has a different effect on torsional vibration response; therefore Desbazeille et al. [19] have studied the torsional mode effects in a twenty-cylinder engine and developed an analytical model with flexible crankshaft for the misfire diagnosis. Moreover, some researchers [20–22] tried to detect the misfires via the angular acceleration of the engine block. Based on the block angular acceleration, the engine output torque can be calculated and the cylinder pressure can be obtained as well. The variation in block angular acceleration can reflect whether there is a combustion fault occurring.

However, when these vibration-based techniques are applied to the engines in a real situation, the misfires cannot automatically be diagnosed from the analyzed vibration signals. Artificial Neural Networks (ANNs) have been chosen as the basis for the next generation of diagnostic effort by the US Navy [23]. A number of researchers have also recommended the use of ANNs as a way of automating the diagnosis of machine faults, and in particular faults in rolling element bearings [24–31]. So ANNs should be a potential solution to the problem of automated diagnostics of different faults in IC engines. A critical issue with ANN applications in machine condition monitoring is the network training, and it not feasible or economical to experience a sufficient number of different actual faults, or generate them in seeded tests, to obtain sufficient experimental results for the network training. Simulation is proving to be a viable way of generating data to train neural networks to diagnose and make prognosis of faults in machines. In reference [32], the main examples given were for simulation of faults in gears and bearings in rotating machines. There was also a small section on faults in IC engines. Desbazeille et al. [19] also simulated the misfires in a large 20-cylinder diesel engine with flexible crankshaft as mentioned above.

In this paper, the measured torsional vibration of the crankshaft and the roll angular acceleration of the engine block are used for the diagnostics of misfires. An ANN based system was developed to automatically diagnose misfires in IC engines and includes the following three phases:

(1) Identification of a fault condition, including fault type.
(2) If a fault, which cylinder?
(3) Given fault type and cylinder, what is the severity?

Multi-Layer Perceptron networks (MLPs) were used to detect whether there is a misifre (MLP1) and to identify the severity of misfire (MLP2). A Probabilistic Neural Network (PNN) was used to identify which cylinder has misfires. This paper embodies new developments and extensions of our former conference papers [33–35]. In our former works [33–35], we tried to use only one MLP (MLP2), with nonlinear log sigmoid transfer function, to identify the severity of the misfires at all speeds/loads, but homed in on the particular severities tested, so the nonlinear (stepped) output does not logically agree with the real situation of identification of continuous variations in the misfire severity, and the classification results are coarse. In this paper, separate MLPs with saturating linear transfer functions were introduced for the severity identification at each speed condition, and therefore the linear output can more accurately indicate the reality of a continuously varying (rather than stepped) condition, and the classification results can be much finer. In order to provide sufficient data for the training of the networks, simulation models were built to simulate different ranges of misfires. During the process of building the simulation models, based on a particular engine, some mechanical and physical parameters, for example the inertial properties of the engine parts and parameters of engine mounts, were first measured and calculated. The thermal and mechanical principles of IC engines were studied and incorporated into the models. The simulation models were also validated and updated by a series of experiments. Advanced digital signal processing techniques were applied to the experimental and simulated vibration signals. The input vectors to the ANNs were extracted/selected features from the processed signals. Finally, the ANN systems were trained using only the simulated data and tested using real experimental cases. Because the simulation models are based on the thermodynamic and mechanical principles of IC engines, the proposed diagnostic system can firstly be expected to be extended to a wider range of faults (in terms of location and severity) than those used to validate the model, and can in principle be adapted for any engine (once again with a relatively small number of validation tests).

2. Vibration measurement and signal processing

The premise of using simulation data to train the networks is that the simulation systems have to be updated and evaluated using at least a small number of experiments. Meanwhile, some mechanical and physical parameters are the required inputs for the simulation models, such as the inertia properties of the engine and its components and the parameters of the engine supports. Therefore the vibration based measurements, and signal processing techniques used are introduced first in this section.