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Fault detection and diagnosis of diesel engine valve trains

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A R T I C L E I N F O

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A B S T R A C T

This paper presents the development of a fault detection and diagnosis (FDD) system for use with a diesel internal combustion engine (ICE) valve train. A novel feature is generated for each of the valve closing and combustion impacts. Deformed valve spring faults and abnormal valve clearance faults were seeded on a diesel engine instrumented with one accelerometer. Five classification methods were implemented experimentally and compared. The FDD system using the Naïve-Bayes classification method produced the best overall performance, with a lowest detection accuracy (DA) of 99.95% and a lowest classification accuracy (CA) of 99.95% for the spring faults occurring on individual valves. The lowest DA and CA values for multiple faults occurring simultaneously were 99.95% and 92.45%, respectively. The DA and CA results demonstrate the accuracy of our FDD system for diesel ICE valve train fault scenarios not previously addressed in the literature.

1. Introduction

The internal combustion engine (ICE) has been the critical component of the automotive industry since its inception. Even as the green energy initiative moves forward, the ICE still holds its value in both conventional and hybrid vehicles. ICEs are composed of a number of mechanical components, each of which may be subject to various mechanical faults. The valve train is a crucial component of an engine which controls the intake and exhaust timing. Faults within the valve train result in a reduction of performance and reliability. The detection of faults in their early stages can be beneficial for the avoidance of larger, more severe faults. Fault detection and diagnosis (FDD) methods are used to monitor a system, identify when a fault has occurred, and identify the type of fault and its location. If a fault can be correctly detected and diagnosed, corrective measures can be applied to repair the fault and reduce any further damage to the system. These are the motivations for our research.

Fault detection and diagnosis systems have been proven to be very valuable for mechanical systems and have received increased recognition over the past few years for automotive applications, e.g. [1–7]. Although the literature on FDD methods is abundant, relatively few papers have been published on FDD systems for ICE valve trains.

A simple technique combining partial sampling with feature averaging for the detection of abnormal valve clearance and combustion gas leakage was proposed in [8]. They mounted four accelerometers on the cylinder head of a four cylinder diesel engine. For the intake valve of cylinder 1, whose normal clearance is 0.3 mm, they induced valve clearance faults of 0.15, 0.6, 0.9, 1.2, and 1.5 mm. They presented tables of feature measurements for the different fault levels, but did not report any classification results. A two-load acoustic method was investigated for a four cylinder diesel engine with two pressure sensors installed in its exhaust system in [9]. Faults in the fuel injector and exhaust valve of one of its cylinders were

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detected by analyzing the pressure waveforms. The normal valve clearance was 0.35 mm. They included example detection results for induced clearance faults of 0.7 mm and 1.7 mm. They did not report any classification accuracy values. In [10] valve clearance faults were induced on one cylinder of a four cylinder diesel engine. They classified the Wigner–Ville distributions of the vibration signal using a probabilistic neural network. The normal valve clearance was 0.30 mm. A 0.50 mm clearance was used as a large clearance fault, while a 0.06 mm clearance was used as a small clearance fault. For eight combinations of faulty and normal cases of the intake and exhaust valves of the single cylinder they obtained classification accuracies as large as 96%. This work was further developed in [11]. Cone-shaped kernel distributions of the vibration signal where classified using a neural network ensemble trained using a novel combined weights adaptive modulation algorithm. For the same fault levels and eight classes as in [10], the classification accuracy reached 99.2%. In [12] a four cylinder diesel engine was equipped with a crankshaft angle sensor, two accelerometers and four in-cylinder pressure sensors. The normal intake valve clearance was 0.40 mm. They induced clearance faults of 0.25 mm and 0.70 mm on the intake valve of one cylinder. They proposed a valve FDD technique based on empirical mode decomposition and the instantaneous variations of the crankshaft's speed. Their results show that the two clearance faults can be distinguished from the normal case. No classification accuracy values were reported. Signals from two acoustic emission sensors were used to study valve clearance faults on a similar ICE in [13]. The normal valve clearance was 0.38 mm. They induced an exhaust valve clearance fault of 0.8 mm in one of the cylinders. From a frequency domain analysis of the acoustic emission signals this fault could be visually distinguished from a healthy engine. No fault FDD algorithm or classification accuracy results were presented. In [14], valve clearance faults were classified for a similar ICE equipped with three accelerometers. Univariate and multivariate analysis of variance algorithms were combined to generate a set of features. Next they compared the accuracy of four commonly used supervised classifiers. The normal valve clearance was 0.25 mm. They induced two valve clearance faults (specifically: 0.30 mm and 0.35 mm) on the intake valve of cylinder 2. For the three classes, they reported classification accuracy rates of about 98% when three features were used. To our knowledge, no papers have been published on FDD of ICE valve spring faults.

A FDD system generally requires signal acquisition, signal processing, and detection and diagnosis. Fault detection is commonly separated in two different methods, signal model-based fault detection and process model-based fault detection. Signal models attempt to detect changes of the signal behavior caused by the process faults. Process models attempt to detect changes in the process behavior by using some mathematical model of the process. This research is focused on fault detection using signal models. Fault detection includes analyzing the measured signals to generate pertinent features. Once these features have been obtained they can be used to diagnose the faults. In this paper, we will make the following contributions to knowledge. We begin by proposing a novel feature generation method. Next, using the generated features as inputs, we compare the experimental performance of five classifiers. Finally, we demonstrate that our FDD system produces accurate results with three unsolved problems from the literature. The first problem is the FDD of diesel ICE valve spring faults occurring separately. The second problem is the FDD of spring faults and clearance faults occurring on multiple diesel ICE valves simultaneously. The third problem is the FDD of multiple faults occurring simultaneously on a single diesel ICE valve.

The organization of this paper is as follows. The test bed and signal acquisition are described in Section 2. Signal processing methods are presented in Section 3. Section 4 describes the new fault detection method as well as other common FDD methods. Experimental results are presented in Section 5. Finally, conclusions are presented in Section 6.

2. Diesel engine experimental test bed

2.1. Instrumented engine and data acquisition system

The engine used for the experiments consists of Kubota Z482-E diesel engine. It is a vertical two cylinder, water cooled, 4-stroke, indirect injection diesel engine. The total displacement is 479.0 cm^3 with a compression ratio of 23:1. It has a continuous power output of 8.05 kW (10.8 HP) at 3600 rpm with a maximum speed of 3800 rpm. The engine is connected to an electric generator (Markon BL105E) acting as a mechanical load. This generator is electrically loaded by a generator test set (Sotcher Measurement Inc. model 627). The engine vibrations are measured using a single accelerometer (PCB model 353B18) mounted on the cylinder head. The angular position of the crankshaft is measured using a BEI optical encoder. The accelerometer and encoder signals are sampled and processed using a PC-based data acquisition (DAQ) system. The DAQ card (National Instruments model PCIe-6353) has a 16-bit ADC resolution and a maximum sampling rate of 1.25 MS/s. The computer is a Windows PC with 8 GB of RAM, and a 3.10 GHz Intel i5 processor. The software was written using LabVIEW version 10.0. A photograph of the instrumented engine and a schematic showing the interconnection of the main test bed components are presented in Fig. 1.

2.2. Introduction to the ICE valve train faults studied

The valve train controls the flow into and out of the combustion chambers. Valve trains typically consist of intake valves, exhaust valves, rocker arms, lash adjusters, pushrods, lifters, camshafts, and valve springs.