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Full Length Article

Analysis of common rail pressure signal of dual-fuel large industrial engine for identification of injection duration of pilot diesel injectors

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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

In this paper, we address the problem of identification of injection duration of common rail (CR) diesel pilot injectors of dual-fuel engines. In these pilot injectors, the injected volume is small and the repeatability of injections and identification of drifts of injectors are important factors, which need to be taken into account in order to achieve good repeatability (shot-to-shot with every cylinder) and therefore a well-balanced engine and furthermore reduced overall wear. This information can then be used for calibration and diagnostics purposes to guarantee engine longevity facilitated by consistent operating conditions throughout the life of the unit. A diagnostics method based on analysis of CR pressure with experimental results is presented in this paper. Using the developed method, the relative duration of injection events can be identified for multiple injectors. We use the phenomenon of drop in rail pressure due to an injection event as a feature of the injection process. The method is based on filtered CR pressure data during and after the injection event. First, the pressure signal during injection is extracted after control of each injection event. After that, the signal is normalized and filtered. Then a derivative of the filtered signal is calculated. Change in the derivative of the filtered signal larger than a predefined threshold indicates an injection event that can be detected and its relative duration can be identified. We present the experimental results and demonstrate the efficacy of the proposed methods using two different types of pressure sensors. We are able to properly identify a change of ≥10 μs (2%, 500 μs) in injection time. This shows that the developed method detects drifts in injection duration and the magnitude of drift. This information can be used for adaptive control of injection duration, so that finally the injected fuel volume is the same as the original.

1. Introduction

Recent technical and computational advances and environmental legislation have stimulated the development of more efficient and robust techniques for the diagnostics of diesel engines. Regulations concerning exhaust-gas emissions have also influenced the development of gas engines. To maintain a high compression ratio of the compression–ignition engine for higher overall engine efficiency, it is necessary to use a dual-fuel (gas-diesel) system.

Diesel engine fuel injection plays an important role in the development of combustion in the engine cylinder. The fuel injection process consists of periodic events from hundreds of microseconds to a few milliseconds, which need to be precisely controlled and continuously monitored in order to run smoothly. Arguably, the most influential component of the diesel engine is the fuel injection equipment: even minor faults can cause a major loss of efficiency of combustion and an increase in engine emissions and noise. The injection systems have been shown to be the largest contributing factor to diesel engine failure [1]. With increased sophistication (e.g. higher injection pressures) being required to meet continuously improving noise, exhaust smoke and gaseous emission regulations, the fuel injection equipment is becoming even more susceptible to failure.

Diagnostics of CR system and especially the diagnostics of CR injectors have been widely studied e.g. [2–13]. Krogerus et al. [4] present a survey of the analysis, modelling, and diagnostics of diesel fuel injection systems. In this publication, typical diesel fuel injection systems and their common faults are presented. The most relevant state of the art research articles on diagnostics techniques and measured signals describing the behaviour of the system are reviewed and the results and findings are discussed. The increasing demand and effect of legislation related to diagnostics, especially on-board diagnostics (OBD), are discussed with reference to the future progress of this field.

Estimation of injected fuel amount has been studied in [5–8]. Hoffmann et al. [5] have developed a model-based injection rate estimator, which takes into account the change in the injection behaviour due to wear and aging effects within the injector's nozzle. Extended

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Kalman filtering (EKF) was used in an observer scheme with the aim of accurately observing the injection rate by estimating the additional parameters of the fault model. Satkoski et al. [6,7] summarize the development of a physics-based fuel flow estimator. Available measurements of piezo stack voltage and rail-to-injector line pressure are used for dynamic state estimation. Estimator results are compared against both open-loop simulation and experimental data for a variety of profiles at different rail pressures, and show improvement, particularly, for more complex multi-pulse profiles. Bauer et al. [8] have developed a model for online estimation of fuel property parameters with the Unscented Kalman Filtering (UKF) method. The model was tested with data from a simulation model and a fuel injection system test rig that was specifically constructed for this purpose. It was found that it is possible to estimate the parameters with negligible bias and that the method is generally suitable.

Using the rail pressure signal for the diagnostics of injector events has been previously studied in [9–12]. Akiyama et al. [9] investigated a method to compensate the difference between an actual amount of injected fuel and a target one. In order to compensate the difference, the influence of pressure wave on fuel amount injected is investigated and injection period will be corrected is realized in an actual engine control system. Meanwhile, pressure wave propagation in common-rail was studied. Isermann et al. [6] developed a model-based fault detection module for CR injection systems. One of the simulated faults was a changed fuel volume through one of the injectors and it was realised by changing the desired injection quantity. The fault detection method was tested on an engine testbed with an Opel Z19 DTH four-cylinder CR diesel engine. By the simultaneous evaluation of several sensor signals, several symptoms in the form of deviations of calculated features can be generated. It was stated that by combining these symptoms and the symptoms calculated in the other fault detection modules and applying classification or inference methods several faults can be diagnosed. Payri et al. [11] studied injection diagnosis through CR pressure measurements, where the objective was to design an algorithm for isolation of the injection events. After the injection event, the rail pressure experiences a drop, which was used as a diagnostic feature of the injection process. Absence of such a drop when the ECU has commanded an injection signal would be a clear indication of a malfunction. Two different test benches were used, namely, a separate CR test bench and an engine test bench. Based on the experiments, the joint use of discrete Fourier transform (DFT) filter (referred to here as ideal filtering) and differentiation of the rail pressure signal seemed to be the best of the studied methods for detection of the injection events from the rail pressure measurement. It was stated that the method is useful even with small injections such as pilot injections. Marker et al. [12] studied the diagnostics of large light fuel oil (LFO) diesel engines where the main diesel injections were investigated. In this research the start and duration of injections are determined based on the pressure signal but each injector has an own pressure sensor close to each injector. This means that each injector incorporates an accumulator with an upstream throttle. In addition, in this case, the injection event is easier to detect than the in case of pilot injections where the injected fuel amount is smaller and the effect on rail pressure is smaller. Of course, this is also rail specific, meaning the dimensions of the rail in use. In [12], filtering is used to attenuate the pressure oscillation, which is due to needle opening and closing events. When these are attenuated, the injection event can be analysed in more detail, in this case determining the injection duration. These frequencies of the pressure oscillations are rail specific.

Mancaruso et al. [13] have analysed pilot injection in a research diesel engine using non-conventional optical diagnostics. The visualization of the pilot injection process was obtained by means of an optical access in the piston head and by the presence of an inclined mirror for the collection of images. The aim of the work was to assess the potential and the suitability of infrared imaging for the investigation of the injection process.

According to the best knowledge of the writers, this is the first publication dedicated to the diagnostics of the CR diesel pilot injectors of dual-fuel large industrial engines using the rail pressure signal. The aim is to diagnose, meaning here to detect injection events and to identify the relative duration of the injection based on analysing the pressure signal of the CR in the case of changed injection duration, i.e. injected fuel volume, being changed for some reason e.g. degradation. The injected fuel volume of diesel pilot injectors is small and the repeatability of injections and identification of drifts of injectors is an important factor. The ultimate goal in our study is to use only one pressure sensor for the diagnostics of multiple pilot injectors e.g. 6 cylinder engines, although in this paper only one injector is presented.

The rest of this paper is organised as follows. The next section presents the utilized CR test system including the studied injector. Then the diagnostics method is introduced followed by the experiments and the analysis results. Finally, the last section summarizes our conclusions.

2. Methodology

2.1. Experimental setup

The CR rail test system, a modified commercial CR system (passenger car), presented in Fig. 1, was utilized to acquire measurement data for studying and developing of diagnostics methods. A second-generation pilot diesel injector of dual-fuel engine was installed to this test system. For this system, a custom-made electronic control unit (ECU) controlling the rail pressure of the CR system and the studied injector was made which made it possible to freely adjust the injection duration, number of injections, time between injections, control currents (boost and hold), pressure level etc. Castrol's diesel injector calibration oil 4113 [14] was used in the CR system.

The pressures of the CR system are measured using high dynamic Kistler pressure sensors (Type: 4067 A 2000), referred to here as p_{RH} and an accurate but lower dynamic Trafag sensor (EPN CR 20 A 1600 bar), referred to here as p_{RL}. A Bosch pressure sensor (original CR system sensor) is used for controlling the rail pressure level, and it is connected to the ECU. The studied injector includes a needle lift sensor (Micro-Epsilon eddyNCDT 3010), which enables accurate detection of needle opening and closing events. The control current of the injector and the pressure regulator were measured using LEM current transducer modules in the ECU. The temperatures were measured from the tank using a Pt100 sensor and from the rail using a K Type thermocouple. Fig. 2 presents a schematic diagram of this CR system, including the installed sensors. The diagnostic method presented in this paper is based on the high dynamic pressure sensor p_{RH} but results are presented also with lower dynamic pressure sensor p_{RL}.

All the measurements were collected using a National Instruments data acquisition card type PCI 6125 using LabView software. The analysed rail pressure data (Kistler, p_{RH}) and the other rail pressure

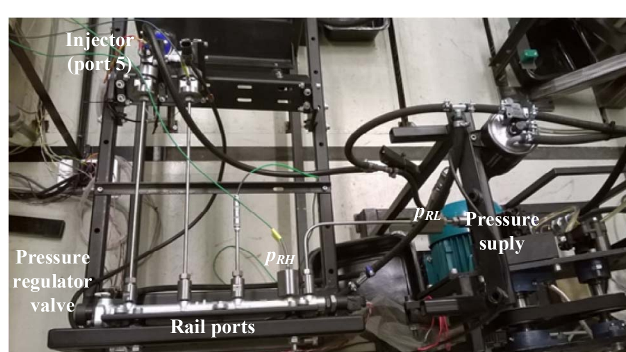

Fig. 1. Experimental setup: CR test system.