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A Double-Injection Control Strategy For Partially Premixed Combustion

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Abstract: Partially Premixed Combustion has shown to be a promising internal combustion concept in terms of engine efficiency and emission levels, however, since the combustion process is partly kinetically controlled, unacceptably high pressure-rise rates could occur at various operating points. A remedy to this problem is the use of a pilot-fuel injection. This paper characterizes double injection effects on combustion through experimental results and presents a double injection closed-loop model predictive control strategy where the combustion phasing is controlled arbitrarily as the pressure rise rate is controlled below a upper bound. Experimental results show promising response times during set-point changes as well as load and speed disturbances.

Keywords: Partially Premixed Combustion, Multiple-Injection Closed-loop Control, Model Predictive Control

1. INTRODUCTION

Partially premixed combustion (PPC) is a low temperature combustion concept that is controlled both by fuel injection and chemical kinetics, it can be viewed as a combination of conventional diesel combustion with the direct controllability of the combustion through fuel injection and homogeneous charge compression ignition with high thermal efficiency and low NO_x and soot emission levels.

Low temperature combustion is an often used name for combustion concepts where the ignition delay is prolonged in direct-injection engines in order to enhance fuel-air premixing. An increased ignition delay gives the fuel more time to penetrate the gas mixture before the combustion starts. This yields locally leaner mixtures during combustion which both reduces the formation of particulate matter and NO_x due to lower combustion temperatures (Musculus, 2006).

PPC has been under research for the past decade at Lund University and is a concept where a combination of early injection timings, high EGR ratios and the usage of gasoline-like fuels has been applied to achieve a sufficient ignition delay while maintaining low fuel consumption (Manente et al., 2010).

It has however been discovered that in single-injection PPC, the long ignition delay gives rise to very high pressure-rise rates, due to violent HCCI-like combustion rates (Manente et al., 2009). High pressure-rise rates indicate for high audible noise levels and could also cause mechanical engine damage, therefore, it has to be kept below certain levels in order to ensure silent and safe operation. Previous research by (Tsurushima et al., 2002) implies that pressure oscillations commonly resulting after violent combustion rates also are able to break insulating thermal-boundary layers which increases heat-transfer flux to the cylinder walls. A remedy to the problem of high pressure-rise rates in PPC is to divide the fuel injection into several injection events, e.g., by having an early pilot injection with less than half of the fuel and a main injection containing the majority of the fuel amount. The pilot injection sets a lean mixture environment that decreases the ignition delay of the main injection and therefore decreases the combustion rates. This technique is also used in conventional diesel engines both to improve low load performance (MacMillan et al., 2009; Osuka et al., 1994) and to decrease emissions and engine noise levels (Eriksson and Nielsen, 2014; Kiencke and Nielsen, 2000).

Both optical OH chemiluminescence experiments (Tanov et al., 2014), and computational fluid dynamics CFD simulation research (Solsjö, 2014) have been performed to better understand multiple-injections light-duty PPC, findings suggest that multiple injections can be used to create stratified mixtures in different air-fuel ratio regions where very lean mixtures created by pilot injections burns more slowly but assists the ignition of fuel-richer mixtures created by the main injection.

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With the increased amount of fuel injection events, the amount of calibration work for optimized engine performance for different loads and speeds grows exponentially, (Meyer, 2011). Therefore it is of course very appealing to find automatic fuel-injection controllers that automatically find fuel-injection timings and fuel distribution among the multiple injections. Previous work on pilot-injection combustion control in low-temperature combustion concepts were presented by (Ott et al., 2013; Eichmeier et al., 2012; Ekholm et al., 2008; Kokjohn et al., 2009).

This paper presents experimental PPC results from a Scania multi-cylinder engine that reflects engine output characteristics w.r.t. double-injection parameters. The experimental results are then used for design of a model predictive controller that is able to track combustion phasing while guaranteeing an upper bound on the maximum pressure rise rate. Controller implementation and experimental performance during engine load and speed variations are also presented.

2. EXPERIMENTAL SETUP

2.1 Engine Specifications

The experimental engine was a Scania D13 heavy-duty diesel engine with engine specifications displayed in Table 2.1. The engine speed was controlled with a 355 kW AC motor that worked both as an engine motor and brake. The engine was boosted with a fixed geometry turbine compressor combination.

Table 1. Engine Specifications

Total Displaced volume	12.74 dm^3
Stroke	160 mm
Bore	130 mm
Connecting Rod	255 mm
Compression ratio	18:1
Number of Valves	4

2.2 Engine control and measurement system

The entire engine control system was programmed with LabVIEW which is a graphical programming environment developed by National Instruments. The real-time system consisted of a NI PXIe-8135 embedded controller (2.3 GHz quad-core processor), NI PXI-7854/7854 R (Multifunction reconfigurable I/O (RIO) with Virtex 5-LX110/LX30 FPGA). The FPGA was considered as a configurable hardware that worked as a flexible AO / DIO, it was also used for AD acquisition.

The in-cylinder pressure was measured with water-cooled Kistler 7061B pressure sensors and was sampled with the Leine-Linde crank angle encoder pulse every 0.2 crank angle degree. Inlet manifold and exhaust pressures were measured with Keller PAA-23S absolute pressure sensors. Inlet manifold and exhaust temperatures were measured with K-type thermocouples.

The fuel injection system was a production Xtra high Pressure Injection (XPI) common-rail injection system for the Scania D13 engines. The common-rail pressure, injection timings, durations and valve positions were controlled from the real-time system using Drivven drivers. The fuel used in the experiments was a mix of 80 volume % gasoline and 20 volume % N-heptane.

The NO_x and HC emission levels were measured with a Horiba measurement system (MEXA-9100E) while soot levels were measured with an AVL micro soot sensor measurement unit.

The heat-release analysis and controller computations were run in MathScript RT Module nodes inside a timed-loop block on the real-time target. The timed loop was triggered by the FPGA once the in-cylinder pressure was sampled. All computations were done using floating point arithmetic.

3. SIGNAL PROCESSING AND DEFINITIONS

3.1 Heat Release Analysis

In order to extract combustion information from the measured in-cylinder pressure p, heat-release analysis was performed every cycle for each cylinder. In order to account for the pressure-sensor offset, the p was pegged w.r.t. to the measured inlet manifold pressure at inlet valve closing (IVC), high-frequency noise on p was attenuated using a zero-phase digital filter.

The heat-release rate $dQ_c/d\theta$ was estimated by treating the combustion chamber content as a single-zone open system. Applying the first law of thermodynamics and the ideal gas law yields

$$\frac{dQ_c}{d\theta} = \frac{\gamma}{\gamma - 1} p \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dp}{d\theta} + \frac{dQ_{ht}}{d\theta}, \tag{1}$$

where V is the cylinder volume and θ the crank angle. The ratio of specific heats $\gamma = c_p/c_v$ depends on the cylinder gas composition and temperature, in this work γ was estimated assuming that p and V satisfy the adiabatic relation

$$pV^\gamma = C \tag{2}$$

γ and C could then be estimated from p and V using linear regression methods. The convective heat-transfer rate from the combustion chamber gases to the combustion chamber wall $dQ_{ht}/d\theta$ was modeled according to (Woshni, 1967) where the in-cylinder temperature T was estimated using the measured intake manifold temperature T_{IM} at IVC ($T_{IM} = T_{\text{IVC}}$) which gives

$$T = T_{\text{IVC}} \frac{pV}{p_{\text{IVC}} V_{\text{IVC}}}. \tag{3}$$

With the accumulated heat release Q obtained from Eq. (1), the combustion timing θ_{50} and the combustion start θ_{10} was computed using

$$x = 100 \frac{Q(\theta_x)}{\max_\theta Q(\theta)},\ x = \{10, 50\}. \tag{4}$$

3.2 The Maximum Pressure Rise Rate $dp_{\max}$

The maximum pressure rise rate $dp_{\max}$ is in this work defined as

$$dp_{\max} = \max_\theta \frac{dp}{d\theta}. \tag{5}$$

Due to the high cycle-to-cycle variation of this signal it has to be filtered in some way in order to be used as a feedback