Applied Energy 119 (2014) 405–416

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Development of a control-oriented model to optimise fuel consumption and NO_X emissions in a DI Diesel engine

S. Molina, C. Guardiola, J. Martín *, D. García-Sarmiento

CMT-Motores Térmicos, Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain

HIGHLIGHTS

- A fast NO_X–bsfc model based on the Response Surface Methodology has been proposed.
- Combustion parameters (burn angles, peak pressure and imep) are key variables to determine NO_X emissions and bsfc.
- Combustion parameters can be modelled from mean variables (faster) or calculated from in-cylinder pressure (more accurate).
- A multi-objective optimisation process based on the model predictions has been performed.

ARTICLE INFO

Article history:
Received 7 May 2013
Received in revised form 3 September 2013
Accepted 8 January 2014
Available online 1 February 2014

Keywords:
Engine performance
In-cylinder pressure
NO_X emissions
Response Surface Methodology
Predictive model

ABSTRACT

This paper describes a predictive NO_X and consumption model, which is oriented to control and optimisation of DI Diesel engines. The model applies the Response Surface Methodology following a two-step process: firstly, the relationship between engine inputs (intake charge conditions and injection settings) and some combustion parameters (peak pressure, indicated mean effective pressure and burn angles) is determined; secondly, engine outputs (NO_X and consumption) are predicted from the combustion parameters using NO_X and mechanical losses models. Splitting the model into two parts allows using either experimental or modelled combustion parameters, thus enhancing the model flexibility. If experimental in-cylinder pressure is used to obtain combustion parameters, the mean error of predicted NO_X and consumption are 2% and 6% respectively, with a calculation time of 5.5 ms. Using modelled parameters reduces the calculation time to 1.5 ms, with a penalty in the accuracy. The model performs well in a multi-objective optimisation, reducing NO_X and consumption in different amounts depending on the objective of the optimisation.

1. Introduction

In the last two decades regulations and market demands have led to improve internal combustion engines (ICE) control systems [1,2], accelerating the evolution of new forms of design. Moreover, next generations of Diesel engines will probably include more sophisticated control systems than those in use today because they will incorporate some combination of variable geometry turbine (VGT), variable rate fuelling, exhaust after-treatment, exhaust gas recirculation (EGR), cylinder pressure sensors and emission sensors among others [3,4].

The variables involved in ICE control can be classified into three types: inputs that can be modified (injection and air management settings), variables that provide information of the real system state (speed, pedal position, pressure and temperature of different fluids at different locations, etc.) and, finally, the engine outputs (performance and emissions). The classical approach for calibration and control is based on lookup tables in which the optimal combination of inputs, obtained from measurements in stationary operating points, is tabulated in terms of engine speed and load [5]. This procedure takes into account the relationship between inputs and outputs to achieve the desired engine response based on a recorded feed-forward control action. However, engine calibration systems based on lookup tables are reaching the limits of their applicability, as they require too much time and effort to be tuned up [6], and they are not optimal under variations in the engine operating conditions.

In this scenario, modern control techniques offer several tools that allow overcoming the stated problem. One of the most efficient approaches is the use of control-oriented predictive models, suitable for the control of systems characterised by a complicated dynamic, multivariable or unstable behaviour [7–10]. If suitable sensors are used, these models can adapt to the engine changes along time [11], ensuring the same operation from the factory

* Corresponding author. Tel.: +34 963877650; fax: +34 963877659.
E-mail address: jaimardi@mot.upv.es (J. Martín).
URL: http://www.cmt.upv.es (J. Martín).

0306-2619/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2014.01.021

Nomenclature

amep	auxiliary mean effective pressure (bar)
B%	burn angles (after top dead centre) (° ATDC)
bmep	brake mean effective pressure (bar)
bsfc	brake specific fuel consumption (g/kW h)
DOE	Design of Experiments
ECU	Electronic Control Unit
EGR	exhaust gas recirculation
fmep	friction mean effective pressure (bar)
F_r	fuel-to-air equivalence ratio (–)
FSN	Filter Smoke Number
HRL	heat release law (J)
ICE	internal combustion engine
imep	indicated mean effective pressure (bar)
$\dot{m}$	mass flow (g/s)
m	mass (kg/str, mg/str)
MPC	Model Predictive Control
n	engine speed (rpm)
p	pressure (bar)
pmep	pumping mean effective pressure (bar)
RoHR	rate of heat release (J/°)
RSM	Response Surface Methodology
SOC	Start of Combustion (° ATDC)
SOI	Start of Injection (° ATDC)
T	temperature (K, °C)
V	volume (m^3)
VGT	variable geometry turbine

Subindex

cyl	in-cylinder
exh	exhaust manifold
f	fuel
inj	injection
itk	intake manifold
m	mean value
main	main injection
max	maximum value
oil	oil
pil	pilot injection

Greek symbols

α	optimisation weighting factor
β	gradient of the merit function near the optimum value

calibration until after several thousand hours of use [12]. This control strategy uses predictive mathematical models of the processes in order to estimate the future behaviour of the system for given control inputs, thus optimising the selection of the control signals [1,6,10,13–17]. In this scenario, in-cylinder pressure provides direct information on combustion development [6,18–22], as peak pressure, indicated mean effective pressure or heat release. Thus, in-cylinder pressure can be used in different engine control applications such as failure detection [22], air mass flow estimation [23], on-line combustion detection [24], exhaust gas recirculation control [13,25], torque estimation [26], noise control [27] or NO_X control [28].

Several works dealing with the combined use of in-cylinder pressure and predictive models for control purposes can be found in literature, ranging from simple to very complex methods. Reitz and Von der Ehe [29] use the pressure peak to set the injection settings in split injection strategies. Leonhardt et al. [22] control the fuel injection and spark timing with a feed-forward emission control strategy based on the pressure peak. Zhu et al. [21] use the pressure peak location, the angle at which 50% of mass is burned (B50) and the pressure ratio in order to find the best spark timing for maximum brake torque. Beasley et al. [30] control the B50 while limiting the peak pressure in the chamber, establishing combinations of these two parameters for engine protection and combustion stability. Win et al. [31] analyse the start of injection, ignition delay, rate of pressure rise, and rate of heat release, to obtain correlations via the Response Surface Methodology (RSM) to carry out a multi-objective optimisation of combustion noise, brake specific fuel consumption (bsfc), HC, soot and NO_X. Several complex models based on neural networks [32], genetic algorithms or fuzzy-logic [12] use the information of the combustion development (derived from the heat release law) along with several engine mean variables for accurate predictions of emission and performance.

This paper proposes a methodology for obtaining an empirical model capable of predicting both the engine consumption and NO_X emissions of a DI Diesel engine. Unlike the proposals of Reitz and Von der Ehe [29], Leonhardt et al. [22] or Zhu et al. [21], the model is not focused on the disturbance of one specific parameter but it considers all the relevant parameters related to intake charge conditions, injection settings and combustion. The use of RSM ensures the model simplicity.

As detailed in the Methodology section, one contribution of the work is splitting the model into two parts: the first is focused on the relationship between inputs and in-cylinder conditions, while the second deals with in-cylinder condition and outputs. This procedure allows following and comparing two alternative paths: modelling the key in-cylinder parameters (imep, p_{max} and burn angles) or obtaining them from the experimental pressure, thus enhancing the model flexibility.

Once bsfc and NO_X models are developed, final part of the paper deals with a multi-objective optimisation of the engine operation. Its objective is finding the best inputs combination that simultaneously minimises bsfc and NO_X, while respecting some constraints.

2. Experimental setup

A scheme of the test cell layout with the instrumentation is shown in Fig. 1. For the sake of accuracy, the experimental tests were carried out in a single-cylinder 0.4 l DI Diesel engine whose 4-cylinder engine version is currently in production. The engine main characteristics are given in Table 1. The engine settings of the reference operating point were taken from the Euro 5 ECU map of the 4-cylinder engine version. The engine was directly coupled to an electric dynamometer that allows controlling the engine speed and load.

The installation includes an EGR conditioning system that takes the gas from the exhaust settling chamber, uses a gas–water heat exchanger to cool and dry it, and then a heater to reach the desired EGR temperature before mixing it with the fresh air. Also, the fresh air can be conditioned to the required temperature. Thus, the intake temperature (after mixing fresh air and EGR) can be accurately controlled according to the experimental test requirements. The exhaust back pressure produced by the turbine in the 4-cylinder engine version is reproduced by a valve in the exhaust system that controls the pressure in the exhaust settling chamber.

The in-cylinder pressure was measured by means of a Kistler 6055B glow-plug piezoelectric transducer with a range between 0 and 250 bar, and a sensitivity of 18.8 pC/bar. The pressure sensor