The Challenge of Fuel Path Control at High Load Conditions

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Abstract: Increasing emissions standards and fuel economy have forced engine designers to incorporate increasing numbers of degrees of control freedom into the engine. Consequently, calibration is becoming progressively more complex where the issue is most acute with diesel engines. This paper presents a project in which a closed loop controller is used in diesel engine fuel path, where no new calibration is required if any variation occurs. This is an initial investigation into diesel engine fuel path control. In order to prove that such a control technology could be developed over the whole speed and torque operating range, a high speed (2050 rpm) and the high torque (357Nm) point are chosen for investigations into control. This represents a challenging engine conditions for the application of control systems because of the limited time available for air supply and the need to complete combustion quickly. At these conditions the control authority is limited and the ability to detect for example small variations in torque and speed are quite limited owing to the high torque conditions. This paper demonstrates a closed-loop control at a high load condition and presents an architecture of controllable injection for a Caterpillar C6.6 engine using predictive control that includes exhaust temperature, of nitrogen oxides (NO\textsubscript{x}) and particulate matters (PM) without changing the fuel quantity.

Keywords: Diesel engine, model predictive control, control system, optimization, optimal control

1. INTRODUCTION

Diesel engines have several significant advantages over spark ignited engines, such as, fuel efficiency, durability, power, and for example very low carbon monoxide emissions. All engines can only operate in an optimal state by using a flexible and precise electronic control technique. Open loop control systems are not ultimately flexible and precise as they cannot compensate for the variations from mass production, aging, fuel properties, and un-measurable environmental factors, such as the humidity the intake air. Therefore, diesel engines with open loop control systems cannot be expected to meet the more stringent fuel and emission requirement. Moreover, diesel engines with open loop control systems require a time-consuming calibration and mapping procedure at the development stage and recalibration for newly developed engines.

More recently closed loop control is being applied to reduce the so-called dispersion effects that are the result of small component and operating variations seen in all engines. Pinson et al simply used closed loop con control meet emissions target (Pinson, 2006).

A great deal of work has been done on the fuel path for spark ignition engines, such as in (Bidan et. al, 1995; Ohata et. al, 1995; Stroh et. al, 2001). For diesel engine fuel path, Carlucci (Carlucci et. al, 2006) use early injection and gas addition to improve engine combustion and reduce pollutant emissions. Model Predictive Control (MPC) has been extensively used in diesel engine air-path control (Iwadare et. al, 2009; Stewart & Borrelli, 2008; Westerlund et. al, 2010). Hsieh et. al (Hsieh et. al, 2009) use nonlinear MPC to control air to fuel ratio profile for lean NO\textsubscript{x} trap regenerations. In this paper, we present an application of constrained MPC to the fuel path control of diesel engine.

Jung (Jung, 2003) showed the frequency responses from EGR and VGT to intake manifold pressure and compressor flow. The air path of a diesel engine responds slowly due to the turbocharger dynamics and inertia. The fuel path of a diesel engine has fast dynamics due to its more direct influence on the cylinder charge. Also in-cylinder dynamics are much faster than the air path dynamics.

Currently the dynamic physical phenomena of the diesel fuel path are not well understood. As a consequence the fuel path control poses more open research questions and the development of fuel path control is a much more difficult task when compared with air path. At high speed and load points the control challenge is significant. Control authority is limited by virtue of air flow and fuel flow being at the extremes of their range. Signal to noise ratio is far worse than at low load conditions, making measurement difficult. The time available for the combustion of fuel is short as is the time available between engine cycles for control decisions. The air system can also approach a choked condition, leading to a difficult, non-linear conditions for air flow control. In this environment the challenge to fuel control is characterized by short timescales, while the need for precise delivery of fuel is increased. In general full load fuelling has been kept simple with just one injection, yet for heavily loaded
application the potential for optimal selection of controlled variables is significant and is the subject for this paper. The fuel path controller which has been proposed for the high load condition, handles multi-input and multi-output and regulates the exhaust temperature and emissions level.

The work reported in (Brahma, et al, 2004) proposes a dynamic model as the basis for a fuel path control system. A state space model is identified for a zone of the speed load map of the engine using commonly available numerical tools (sub-space (Ljung, 1999), for example). This paper adopts the similar modelling strategy.

In the work reported in this paper the aim has been to meet emissions and fuel consumption goals in the same way as has been achieved for passenger cars. This aim is addressed by controlling the fuel injection parameters without changing the fuel quantity as the torque and speed are held constant by the outer-loop controller. The fuel path controller is an inner-loop control.

This is an initial investigation into diesel engine fuel path control. In order to prove that such a control technology could be developed over the whole speed and torque operating range, a high speed (2050 rpm) and the high torque (357Nm) point are chosen for investigations into control. This represents a challenging engine conditions for the application of control systems because of the limited time available for air supply and the need to complete combustion quickly. At these conditions the control authority is limited and the ability to detect for example small variations in torque and speed are quite limited owing to the high torque conditions. The work reported in the paper demonstrates an architecture of controllable injection that meets the needs of multi-cycle control in a form of predictive optimal control that includes objectives to address exhaust gas qualities and engine output. If this control approach is adopted in practical application, virtual sensors based on neural networks could be used for the emissions and exhaust temperature measurement (Maass, et al, 2009).

This paper is organized as follows: Section 2 introduces the experiment facility. Section 3 describes the control model. Section 4 introduces closed-loop control concept. Section 5 presents the real time control results, followed by discussion in Section 6 and Conclusion in Section 7.

2. EXPERIMENTAL FACILITY

The engine calibration used for this work produces up to 159kW at rated speed (2200rpm) with peak torque of 920Nm occurring at 1400rpm. The engine has been modified with a high pressure loop EGR system and a Honeywell servo-actuated variable geometry turbine.

The engine’s original ACERT™ (Caterpillar® trademark: Advanced Combustion Emissions Reduction Technology) fuel injection control strategy provides multi-shot injection capability using a number of injection characteristics; start of main injection, shot duration, dwell between each shot, fuel ratio-between each shot and fuel rail pressure. In this set-up, the engine control unit (ECU) has been completely removed from any engine control responsibilities; its function limited to providing an electrical power source for specific engine sensors. The detailed facility was described in (Winward et al, 2010). Fig.1 shows the C6.6 engine and operator station.

The closed loop control algorithms for control inputs, such as, the start of injection and rail pressure, are built using Simulink models. The technique has been developed to link the input/output of the Simulink controllers to the Labview real time injector control software.

![Instrumented engine and the operator station](image)

A Simulink model is built into a National Instruments real time system compatible dynamic link library (dll) using the National Instruments Simulation Integration Toolkit. The dll is copied to the real time system and loaded and executed when the injector hardware control software is initialised. Inputs from the injector control software (speed, load etc.) are routed directly to the dll and the embedded algorithm computes the required variables, such as, start of injection timing and rail pressure. This technique provides a deterministic implementation of a Simulink based controller.

3. CONTROL MODELS

The MPC (model predictive control) formulation is employed (Maciejowski, 2002) and is based on a linear, discrete-time state-space model of the plant. The proposed model can be expressed by the following equations, which is based on the assumption of a linear model of high order (Brahma et al, 2004). Its structure is physically motivated and its parameters are estimated during the system identification process, which is a typical grey-box model:

\[
\begin{align*}
x(k+1) &= Ax(k) + Bu(k) \\
y &= Cx
\end{align*}
\]  

where \(x(k)\) is the state vector at time \(k\), \(u(k)\) is the vector of inputs and \(y(k)\) is the measured outputs, for example, in this paper,

\[
\begin{align*}
u &= \{\text{soi pressure ratio}\} \\
y &= \{T_e, \text{NOx, PM}\}
\end{align*}
\]

where, soi expresses start of injection timing, pressure expresses common rail pressure, ratio is the ratio between the main and pilot injection, \(T_e\) is the exhaust temperature, PM is the particulate matter and NOx is the nitrogen oxide concentration in the exhaust gas. Due to the impact of
exhaust temperature on the temperature of the exhaust and after-treatment system it is regarded as one of the most important controllable parameters in diesel engines.

The state space model is identified at the speed of 2050 and speed at 375 Nm. In this work, the prediction error method (PEM) function of MATLAB’s System Identification Toolbox (2007b) which uses an iterative prediction-error minimization method, was used to obtain the model matrices. PEM uses optimization to minimize the cost function, defined as follows for scalar outputs:

\[
\text{cost} = \sum_{i=1}^{N} e^2(t)
\]

where \(e(t)\) is the difference between the measured output and the predicted output of the model.

4. CONTROL DEVELOPMENT PROCESS

The closed-loop system in Fig.2, which takes feedback signals from the engine that includes particulate matter and nitrogen oxide concentration in the exhaust gas, exhaust gas temperature, will compensate for variations in the engine parameters, reducing the complexity of the calibration procedure and require no recalibration time.

The function of an engine is controlled principally by the manner in which fuel is burnt in the cylinders. The combustion process results in heat release and determines the torque and exhaust emissions. The critical parameter in control of engines is the heat release that results from the combustion. Heat release is controlled by means of regulating the flow of fuel into the combustion process. The fuel control is achieved by choosing injection timing, rail pressure and fuel ratio, which is the fuel amount ratio between the main and the total fuel injection (Fig.2). The total fuel amount is equal to the sum of the main and pilot fuel amount.

![Controller](image)

Fig.2 The fuel path controller

Multivariable control-oriented method use outputs of the exhaust temperature, NOx and PM with respect to the inputs of start of injection timing, rail pressure and the fuel quantity ratio between the main and pilot as the control inputs. The influence of injection timing towards the reduction of emissions is well known (Noguchi et al., 1996). Hence, it is quite natural to include fuel timing as the control input vector.

Model Predictive Control (MPC) (Maciejowski, 2002) has been investigated for its ability to optimize engine system behaviour. MPC uses a dynamic model of the system to be controlled and is based on iterative, finite horizon optimization of an engine system model. At a time \(t\) the system characteristics of interest are sampled and an algorithm calculates a cost-minimising control strategy step for a short time horizon \(h\) in the future: \([t, t + h]\).

A real time calculation takes place, which examines the trajectory of the system characteristics. At time \(t + 1\), the engine system is sampled again and the next controls step is calculated and trajectory predicted. The resulting behaviour which is optimal according to a cost function can be adapted as the engine ages and changes its behaviour.

The control model is composed of Equation (1) and (3).

\[
z(k) = C_x x(k)
\]

\(z(k)\) is vector of outputs which are to be controlled to satisfy some constraints, or to particular set-points, or both.

A Kalman filter is used for state vector estimation with the following formulation (4):

\[
\begin{align*}
\hat{x}(k+1 | k) &= A \hat{x}(k | k - 1) + Bu(k) + L e(k | k) \\
\hat{y}(k | k - 1) &= C_y \hat{x}(k | k - 1) \\
\hat{z}(k | k - 1) &= C_z \hat{x}(k | k - 1)
\end{align*}
\]

where \(\hat{x}(k+1 | k)\) is the estimate of the state at future time \(k+1\) is based on the information available at time \(k\), \(\hat{y}(k | k - 1)\) is the estimate of the plant output at time \(k\) based on information at time \(k-1\), \(L\) is the Kalman filter gain matrix, and \(\hat{e}(k | k)\) is the estimated error defined as: \(\hat{e}(k | k) = y(k) - \hat{y}(k | k - 1)\). The cost function is defined as follows:

\[
\begin{align*}
V(k) &= \sum_{i=1}^{h} || \hat{z}(k+i | k) - r(k+i | k) ||^2 Q(i) + \\
&+ \sum_{i=0}^{m-1} || \Delta u(k+i | k) ||^2 R(i)
\end{align*}
\]

where the prediction and control horizons are \(h\) and \(m\), respectively, \(Q(i)\) and \(R(i)\) are output weight and input weight matrices, respectively. The cost function is subject to the inequality constraints:

\[
\begin{align*}
u_{\text{max}}(k) &\geq u(k+i-1 | k) \geq u_{\text{min}}(k) \\
\Delta u_{\text{max}} &\geq \Delta u(k+i-1 | k) \geq \Delta u_{\text{min}}(k) \\
z_{\text{max}}(k) &\geq z(k+j | k) \geq z_{\text{min}}(k)
\end{align*}
\]

where \(i=1,2,...,m\) and \(j=1,2,...,h\).

This formulation borrows from the constrained algorithm presented in (Maciejowski, 2002). The cost function \(V\) in Equation (5) is minimised by the predictive controller and penalises deviations of the predicted controlled outputs \(\hat{z}(k+1 | k)\) from a reference trajectory \(r(k+i | k)\) and also...
penalises changes $\Delta u(k+i | k)$ in the future manipulated inputs.

For example, in some cases, predicted controlled outputs $z(k+1 | k)$ are exhaust temperature, NO$_x$ and PM. The reference trajectory $r(k+i|k)$ is the set point of exhaust temperature, NO$_x$ and PM. The manipulated inputs are start of injection of timing, rail pressure and fuel ratio.

A constrained predictive controller is particularly important in fuel path control. The constraints will limit manipulated inputs, such as, the rail pressure, injection timing, and fuel ratio, so that there is no risk of engine components being exposed to abnormal loads and conditions.

5. REAL TIME CONTROL FOR THE HIGH LOAD CONDITION

The predictive controller is implemented and using interface block sets communicates with the NI PXI system and FPGA card to directly control the fuel injection equipment. Exhaust temperature, NO$_x$ (ppm) and opacity ( % ) are measured and are returned to the controller as feedback parameters.

Fig.4 shows the results of three inputs and three outputs control results. Exhaust temperature, NO$_x$ and PM are controlled by start of injection timing, rail pressure and fuel ratio as shown Fig. 3. For this case, NO$_x$ and PM are read using a CAN communication link. Because of the indeterminate nature of the operation of CAN, there is the potential for introducing noise. However, the nature of the control performance is demonstrated.

![Fig.4 Control performance using start of injection timing, rail pressure and fuel ratio to control exhaust temperature, NO$_x$ and PM](image)

Fig.3 Model fuel path control inputs behaviour for model set point change: start of injection, fuel rail pressure and fuel ratio.

The tests of the controller have demonstrated that a closed loop control to modulate exhaust temperature, NO$_x$ and PM while maintaining torque is feasible at high load and speed point. Further work will expand the whole working range by allocating controllers to different load and speed points and employing a gain schedule technique.

6. DISCUSSION

Recent work on the application of control systems to engines has focused on air supply. Numerous approaches to the multi-variable control of air and EGR flow rates have been reported and demonstrated (Ammann et al, 2003; Jankovic & Kolmanovsky, 2000; Jung, 2003).

Diesel fuel path control by comparison has been neglected and it has been the aim of this work to demonstrate an
application of optimal control methods in the management of important exhaust system variables.

The motivation for our work is the importance of the control of exhaust conditions. The work reported in this paper is at a high load condition which creates a demanding environment for the controller. One reason for the adoption of MPC is that we could explicitly use constraints in the formulation of the controller so that all the parameters in the fuel path are constrained. The positioning of events in time mean that fuel pulses must be separated and that a single pulse cannot have too much of the total of the fuel to be injected in any one cycle. The rail itself creates constraints and introduces dynamics and this phenomenon has not yet been fully explored in this paper. The operation of the rail potentially imposes constraints in subsequent injections through the creation of standing waves.

The controller demonstrates that an optimal control of the fuel path is feasible and sets the scene for the continuing development of optimal techniques. The work reported in this paper represents the first step in a more comprehensive project to demonstrate fuel path control working across the load and speed range of a medium duty diesel engine.

7. CONCLUSION

Fuel path control is formulated on the basis of a linear state space model.

Constrained predictive control methods in MIMO modes can be used to control NOx, PM and exhaust temperature and at the same time to keep the engine in a safe status in high load and speed operating point.

Successful application of control in this context holds considerable promise for developing the controllers in the whole working operation points and after-treatment management and a reduction in calibration effort.

ACKNOWLEDGEMENT

The reported work has been conducted during a project that is co-funded by the U.K. Technology Strategy Board's Collaborative Research and Development program, following an open competition (Grant Reference, TP/3/DSM/6/1152). The Technology Strategy Board is an executive body established by the U.K. Government to drive innovation. It promotes and invests in research, development and the exploitation of science, technology and new ideas for the benefit of business – increasing sustainable economic growth in the UK and improving quality of life.

The authors wish to thank the Technology Strategy Board and its representative, Mr Ian Massey for support throughout the project. Thanks is also due to Dr. Robert M. McDavid Mr. Paresh Desaid and Mr. Tom Langley of Caterpillar Inc. for their technical support and encouragement, Mr. ED Winward and Ms Zhijia Yang of Loughborough university for the experiment facility help.

We would also like to thank Mr Pete Haug of Honeywell Turbo Systems, Torrance California for consistent help thought the project with turbocharger hardware and technical support.

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