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Development of a Fuel Quantity-based Engine Control Unit Software Architecture

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ABSTRACT

Conventionally diesel engines are controlled in open loop with maps based on engine speed and throttle position wherein fuel quantity is indirectly fixed using the rail pressure and injection duration maps with engine speed and throttle position as the independent variables which are measured by the respective sensors. In this work an engine control unit software architecture where fuel quantity is directly specified in relation to the driver demand was implemented by modifying the control logic of a throttle position based framework. A desired fuel quantity for a given engine speed and throttle position was mapped from base line experiments on the reference engine. Injection durations and rail pressure required for this quantity was mapped on a fuel injector calibration test bench. The final calculation of injection duration in the new architecture is calculated using the fuel injector model. This enables determination of fuel quantity injected at any moment which directly indicates the torque produced by the engine at a given speed enabling smoke limited fuelling calculations and easing the implementation of control functions like all-speed governing.

Keywords: ECU software architecture; Fuel quantity; Calibration

1. INTRODUCTION

Combat vehicles including battle tanks deployed in the hazardous field operation in dusty environments, high ambient temperatures and rough terrains continue to have diesel engines for powering them. Current mechanical fuel injection systems in these engines are inferior in its performance when compared to their electronically controlled common rail injection (CRI) counterparts. Adaptability to any non-standard conditions by applying correction factors in the software of the engine control unit for the fuel quantity injected is essential for proper operation of a diesel engine. In addition in a combat vehicle various limp home modes and other diagnostic features are incorporated in the control logic in the ECU for enhancing the reliability and achieving required performance standards. These can be achieved in CRI diesel engines with proper control software being embedded in the engine control unit (ECU). Control logic for the ECU which can be easily adapted to any CRI diesel engine to be used in combat vehicles was successfully achieved by Indian Institute of Technology Madras, Chennai[1]. ECU software architecture initially developed was based on a conventional throttle position based framework wherein a reference diesel engine was controlled in open loop with maps based on engine speed and throttle position. In this method the fuel quantity is indirectly fixed using the rail pressure and injection duration maps with engine speed and throttle position as the independent variables which are measured by the respective sensors. Although this method is easy to implement, the torque of the engine need not be proportional to the injection duration as shown in Fig. 1. In such a case it is very difficult to infer the torque from the injection duration. However, the quantity of fuel injected can indicate the torque on the engine which then can be used for other control functions.

Figure 2 indicates that the torque is proportional to the fuel quantity at all engine operating conditions wherein the speed, fuel injection duration, rail pressure and boost pressure are different. Hence, fuel quantity can enable virtual torque sensing.

Heintz[2], *et al.* introduced a central torque demand effecting the main actuator set points; mainly injection and

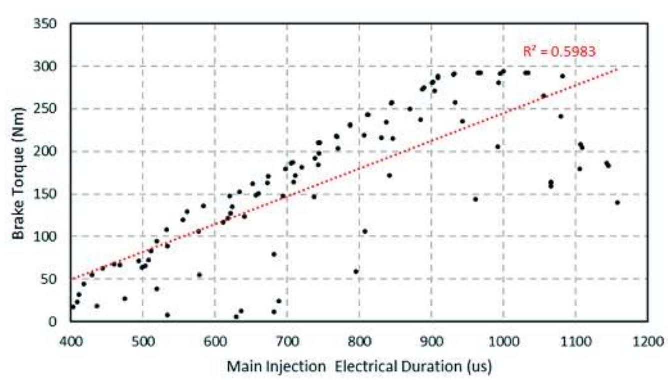

Figure 1. Torque *vs* injection duration.

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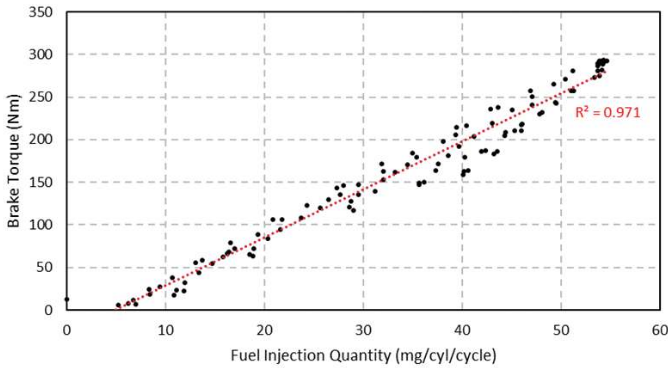

Figure 2. Torque *vs* injection quantity

ignition events in a gasoline engine considering driver torque demand, friction and pumping losses, internal sub-functions like idle speed control and high idle speed governing and torque requirements from auxiliary systems. Byungho[3], *et al.* have developed a torque estimation model for torque based control by using crankshaft speed variation. To achieve accurate engine-brake torque control, Shinya[4], *et al.* focused on indicated torque and since it is shown experimentally that there is a linear relationship between indicated torque and intake air, authors have controlled intake air instead of indicated torque.

For implementing a torque based architecture, target torque for a given engine speed and throttle position as well as fuelling quantity for this target torque and engine speed have to be arrived at. For a new project, vehicle and engine level simulations[5] will enable one to arrive at the preliminary target torque and fuelling quantity for the ECU set points.

2. OBJECTIVES

The objectives of this work is to develop and implement fuel quantity based architecture in an open engine controller for a diesel engine with specifications as shown in Table 1 and validate the same under steady and transient conditions.

Table 1. Engine specifications

Type	CRI with VGT
Rated power	120 hp
Rated speed	4000 rpm
Max torque	280 @(2400-2800 rpm) Nm
No of cylinders	4
Cylinder config.	I4
Swept volume	2.179 *l*
Power density	55.07 hp/l
Bore	85 mm
Stroke	96 mm

3. ECU SOFTWARE ARCHITECTURE

3.1 Throttle Position based Framework

Figure 3 shows an outline of the conventional throttle position based framework where injection scheduling (the pattern of injections required out of 3 pilot, 1 main and 2 post), pilot timing and duration, main timing and duration,

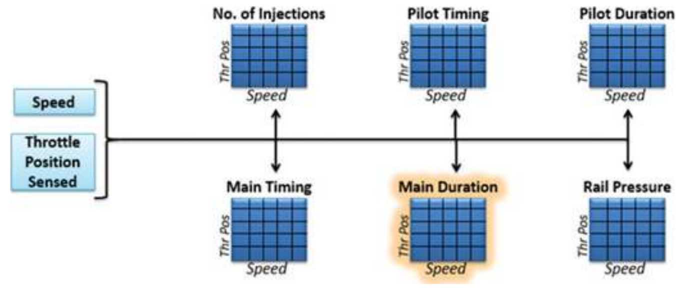

Figure 3. Throttle position based framework.

and rail pressure are specified as maps with engine speed and driver throttle demand in per cent of position as independent variables. The fuelling quantity of an operating point is indirectly fixed by the rail pressure and injection durations at that point. Hence, the fuelling is an unknown quantity in the ECU control logic making it difficult to implement fuelling corrections or special functions like all speed governing.

3.2 Fuel Quantity based Framework

In the current work, fuel quantity which was mapped from the baseline steady state experiments at every 200 rpm from 800 rpm to 4400 rpm and every 10 per cent throttle position was used as the target set point for a given engine operating condition as in Fig. 4. Injection durations were arrived at by mapping the fuelling quantities for a given rail pressure and injection duration in the fuel injection calibration test bench. Some of the existing maps like rail pressure and injection timings were used as it is in the original logic. The final calculation of injection duration in the new architecture is processed through the fuel injector model to find the duration. This enables determination of fuel quantity injected at any moment which directly indicates the torque produced by the engine at a given speed enabling smoke limited fuelling calculations. During calibration this architecture allows the other parameters like injection timings to be adjusted automatically based on the demanded fuel quantity.

4. OPEN ENGINE CONTROLLER

An open engine controller hardware was required to implement the developed control strategies in the form of software codes. FlexECU DI from M/s Etas India was identified as the most suited one for this work. It is a production

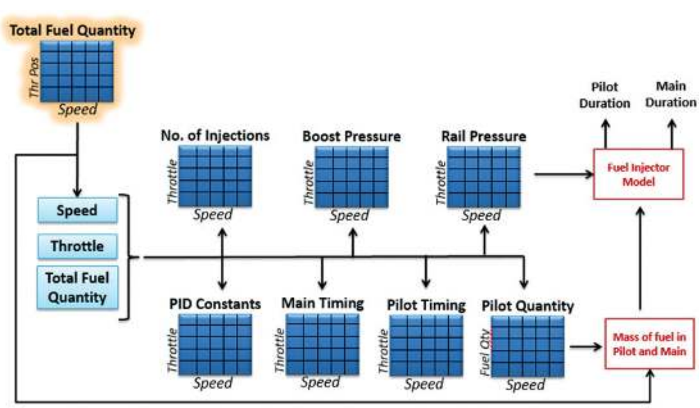

Figure 4. Fuel quantity based framework.

intent ECU with real time operating system (RTOS) and with dedicated drivers for peak and hold type of solenoid diesel injectors, pulse width modulated (PWM) outputs and standard analog and digital inputs and outputs. Power supply module with fuses were made in-house. The controller uses ES592 module to communicate with PC via controller area network (CAN) bus and ES650 module for any additional sensor integration which is not a part of the control algorithm. The controller uses only the standard engine sensors and actuators used by the reference engine controller and a wiring harness was made in-house to communicate with the sensors and actuators. The software logics were coded in Matlab/Simulink using the standard Simulink library blocks in addition to the ETAS provided library blocks which were used for interfacing with the ECU hardware. Details of development, tuning and validation of the important software modules used in this work can be found in[1]. The models developed in Simulink were compiled using E-Hooks compiler and A2l and Hex files were created to be flashed on to the ECU. ECU flashing was implemented using INCA software via the ECU's CAN bus connected to the ES592 module. INCA software was used to monitor the ECU parameters and also to edit the ECU maps and variables in real time whenever required. Any modifications made to the ECU during real time operation of the engine would however need to be flashed on to the ECU for permanent storage.

5. FUEL INJECTOR CALIBRATION EXPERIMENTS

Fuelling quantity for a given rail pressure and injection duration was mapped on a fuel injector calibration test bench (Fig. 5). This dedicated fuel injection test bench was built in-house with similar components as in the reference engine with a layout as shown in Fig. 6. This consists of a high-pressure fuel pump with inlet fuel metering valve (IMV) driven by a three phase AC motor which was controlled using a variable frequency drive (VFD). Fuel from a tank was suitably filtered and supplied to this high-pressure pump, which in turn delivers fuel to a common rail pump with Rail Pressure Regulation valve which was controlled and independently set to safe operating pressures using a National Instruments controller (for safety). The common rail was also connected to solenoid fuel injectors and the setup also generates speed signals as in the reference engine. The entire setup was interfaced to the open engine controller (Flex-ECU) with in-house developed software and the rail pressure controller module was calibrated.

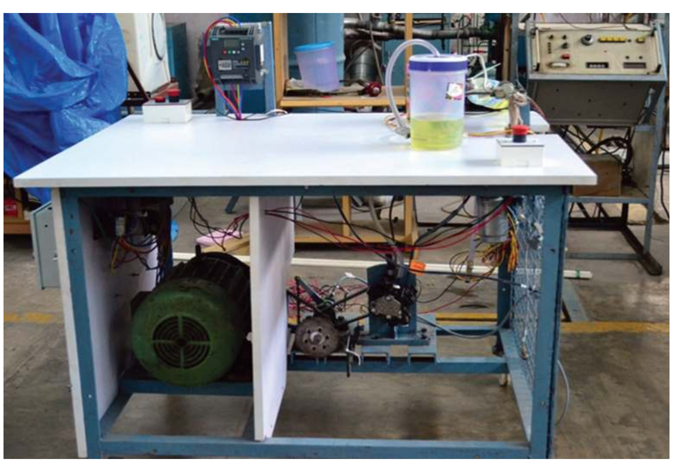

Figure 5. Fuel injector calibration test bench.

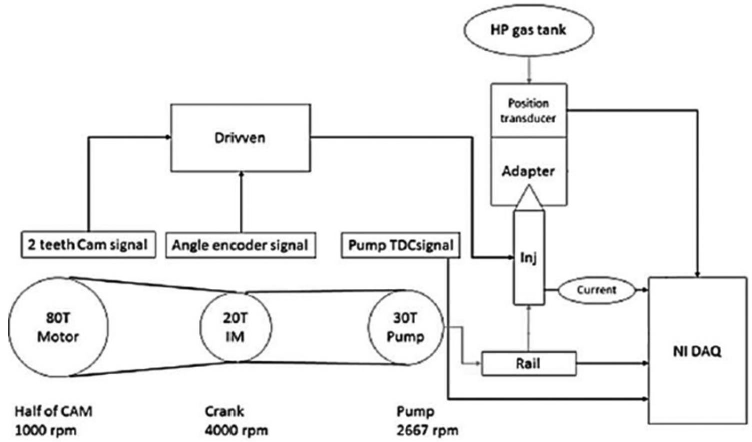

Figure 6. Fuel injector calibration test bench layout.

Experiments were carried out using Flex-ECU to inject a set number of injections for a given rail pressure and injection duration. This was repeated for different rail pressures ranging from 300 bar to 1600 bar and for injection durations from 250 µs to 1600 µs in discrete steps. Every operating point was repeated 3 time for better accuracy. Fuel quantities measured and mapped were corrected for experimental fuel temperature. The fuelling in the complete operating range is as shown in Fig. 7. For low injection duration and rail pressure it is evident that fueling is non-linear which demanded further calibration of pilot quantity on the test bed so as to remove any interpolation related errors leading to non-injection. Also, pump speed was varied from 800 rpm to 1600 rpm with constant rail pressure (300 bar) and constant injection duration (1000 µs).

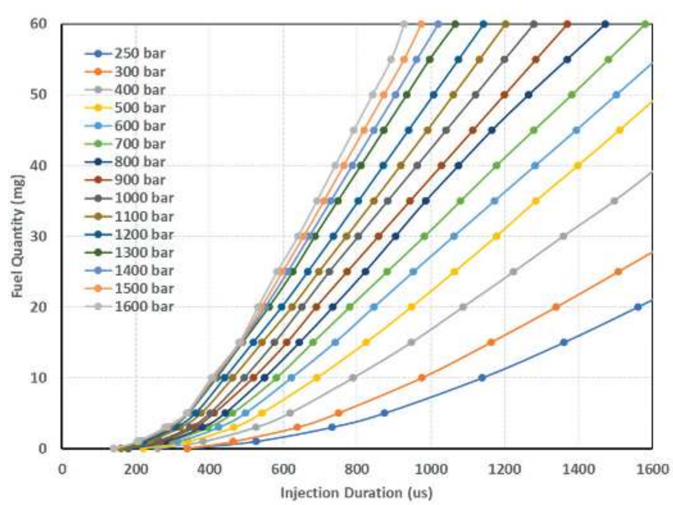

Figure 7. Fuel quantity mapped.

6. VALIDATION OF THE MODEL

Steady and transient experiments were conducted on a state of the art 250 kW transient dynamometer test bed with reference engine integrated as shown in Fig. 8.

Results of a transient test at a constant speed of 1800 rpm

Figure 8. 250 kW transient dynamometer facility.

and load transient from 35 per cent to 80 per cent of throttle position are as given in Fig. 9 and Fig. 10 for rail pressure and boost pressure control.

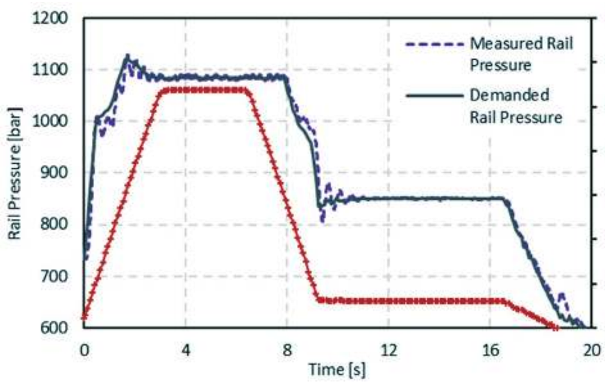

Figure 9. Fuel quantity based architecture - Rail pressure control.

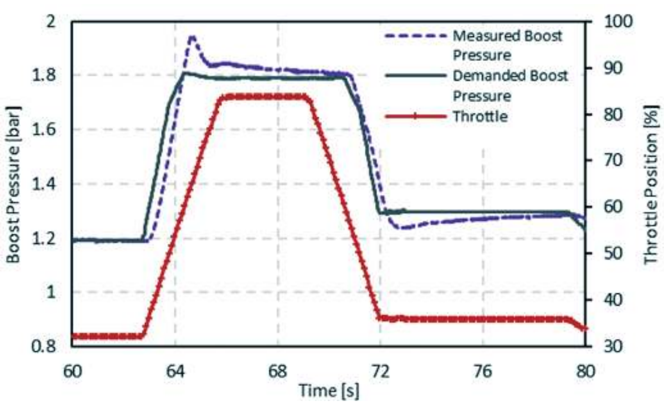

Figure 10. Fuel quantity based architecture boost pressure control.

Similar transients tested with the throttle position based architecture at a constant engine speed of 1800 rpm are also as shown in Fig. 11 and Fig. 12.

Here closed loop control of rail pressure and boost pressure based on the actuation of IMV and VGT respectively are given for a load transient from 30 per cent to 60 per cent of throttle position. It is clear that in both architecture set rail pressure and boost pressures are met by the Engine control unit software.

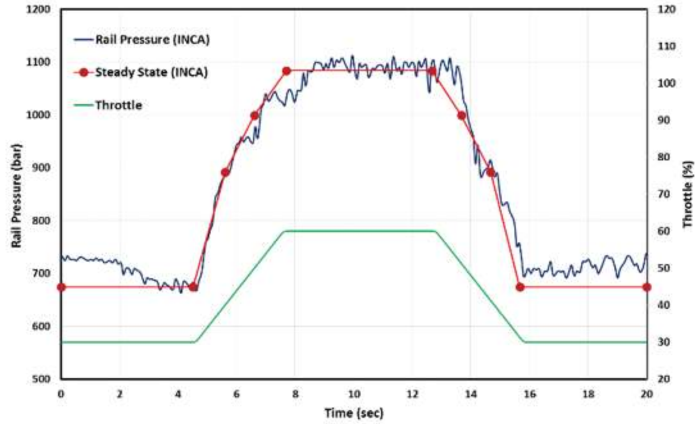

Figure 11. Throttle position based architecture : Rail pressure control.

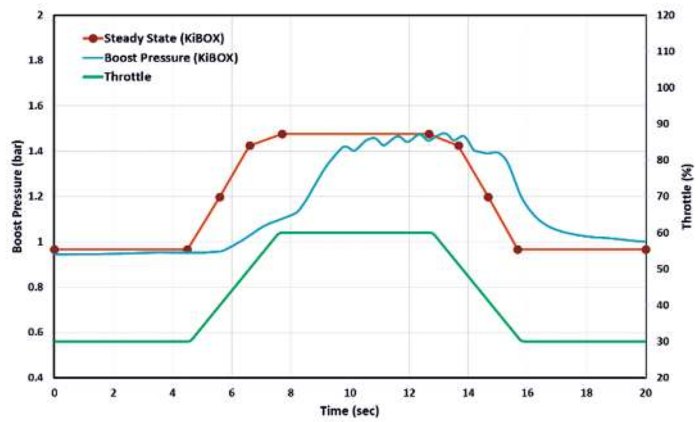

Figure 12. Throttle position based architecture : Boost pressure control.

7. CONCLUSIONS

An existing throttle position based ECU architecture was converted to fuel quantity based architecture by fuel injector characterisation. Fuel injector characterisation experiments were carried out on a fuel injector test bench with fuelling quantity mapped for various rail pressure and injection durations. This has enabled the development of the fuel quantity based ECU architecture which was successfully implemented in a 120 hp reference engine and validated in steady and transient operation in a transient dynamometer facility. This architecture is suitable for adapting the injection requirements for multi-mode governing operation including all-speed governing and various non-standard operating conditions like high altitude and high temperature consisting of fuel de-rating with minimal vehicle calibration effort. Since the architecture is fuel quantity based it can be scaled up to suit other capacities by increasing the fuel delivery and incorporating the matched injector with its characteristics.

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Contribution in the current study, he has set-up the test facility, implemented the algorithm and carried out the experimentation of the engine in the study.

Mr Pramod M. Paul, completed his Bachelor's in Mechanical Engineering at Indian Institute of Technology, Madras. Currently pursuing his Master's in Automotive Engineering at RWTH Aachen University, Germany and also working as student worker in FEV Europe GmbH.
Contribution in the current study, he has developed ECU application software for the engine in the study.

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Contribution in the current study, he has arrived at the control algorithm of the engine in the study and guided the overall work.

Mr Anand Mammen Thomas, completed Bachelor's in Mechanical Engineering from College of Engineering, Trivandrum, in 2007 and currently pursuing Master's in Mechanical Engineering at IIT Madras. Presently working as Scientist `C' in Research & Innovation Centre, IIT Madras Research Park, Chennai and is working on control strategies for a common rail direct injection armoured fighting vehicle engine.
Contribution in the current study, he has supported the instrumentation and experimentation of the engine in the study.

Mr N.S. Prasad received his Bachelors in Mechanical Engineering from the university of Madras in 2004. Currently, he is a Scientist 'E' in DRDO-Combat Vehicles Research and Development Establishment, Chennai. His research is mainly focussed on design of diesel engines for armoured fighting vehicles (AFVs).
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Mr A. Kumarasamy, received his Masters from IIT Madras, Chennai in 1995. Working as Scientist `G' in DRDO-Combat Vehicles Research and Development Establishment, Chennai and heading Engine Division.
Contribution in the current study, he has initiated this study, reviewed and guided the work and contributed to the integration of the cooling system of the engine under study.