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Development and Demonstration of Control Strategies for a Common Rail Direct Injection Armoured Fighting Vehicle Engine

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ABSTRACT

The development of a controller which can be used for engines used in armoured fighting vehicles is discussed. This involved choosing a state of the art reference common rail automotive Diesel engine and setting-up of a transient engine testing facility. The dynamometer through special real-time software was controlled to vary the engine speed and throttle position. The reference engine was first tested with its stock ECU and its bounds of operation were identified. Several software modules were developed in-house in stages and evaluated on special test benches before being integrated and tested on the reference engine. Complete engine control software was thus developed in Simulink and flashed on to an open engine controller which was then interfaced with the engine. The developed control software includes strategies for closed loop control of fuel rail pressure, boost pressure, idle speed, coolant temperature based engine de-rating, control of fuel injection timing, duration and number of injections per cycle based on engine speed and driver input. The developed control algorithms also facilitated online calibration of engine maps and manual over-ride and control of engine parameters whenever required. The software was further tuned under transient conditions on the actual engine for close control of various parameters including rail pressure, idling speed and boost pressure. Finally, the developed control strategies were successfully demonstrated and validated on the reference engine being loaded on customised transient cycles on the transient engine testing facility with inputs based on military driving conditions. The developed controller can be scaled up for armoured fighting vehicle engines.

Keywords: ECU development; Diesel engine control; Common rail direct Injection; Armoured fighting vehicle engines; Transient engine testing; Closed loop control

1. INTRODUCTION

The future armoured fighting vehicle (AFV) engines are expected to be powered by common rail direct injection diesel engines. These engines are usually equipped with many sensors and actuators for precise control of fuel and air. The engine's electronic control unit (ECU) serves as the brain of the system, taking inputs from the sensors to precisely control actuators, thereby resulting in an optimised performance of the entire system[1-2]. These controllers use sophisticated control algorithms which are proprietary in nature and hence very less information is available in the open literature. In addition, the military specific requirements of an engine are quite different from civil requirements and hence necessitate the establishment of a dedicated development procedure[3].

In view of the above requirements, the development, testing and validation of engine controllers for use in AFV applications has been taken up at the Internal Combustion Engines Laboratory, Indian Institute of Technology Madras and a dedicated facility has been set up as part of this work. The task includes the selection of a state-of-the-art multi-cylinder common rail diesel engine with advanced features like turbocharger with variable geometry turbine (VGT), intercooler and exhaust gas recirculation (EGR), as the reference engine. The reference engine was instrumented for combustion and turbocharger diagnostics on a steady state dynamometer controlled by its stock ECU. The fully instrumented engine was then moved to an advanced engine testing facility with transient dynamometer, which was set up in parallel as part of this work and the bounds of operation of the reference engine were determined.

An open engine controller hardware was procured from M/s ETAS India, to provide a platform for development and testing of the engine control algorithm. The engine speed signals were initially simulated using dedicated hardware setup and interfaced with the engine controller to calibrate the engine position management (EPM) module of the controller. The developed Fuel Rail Pressure controller and Fuel injection modules of the open engine controller were also tested on a

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dedicated and in-house developed fuel injection testing set-up which had similar hardware configurations as the reference engine. The engine controller with the in-house developed software modules was then interfaced with the reference engine for its stand-alone control. The reference engine was loaded under steady and transient conditions and various software modules of the controller were tuned for optimum response and performance of the engine. The developed controller was also tested and demonstrated on the developed transient engine testing facility under military specific driving cycles. The control algorithm thus developed would be scaled up for AFV engines.

2. REFERENCE ENGINE

A survey of commercially available state-of-the-art Common Rail Diesel engines was done to identify a suitable reference engine. The mHawk120 Diesel engine from M/s Mahindra & Mahindra was identified as the most suitable one for this development work. The detailed specifications of the reference engine are given in Table 1.

Table 1. Technical specifications of the reference engine

Rated power	120 hp @ (4000 rpm)
Max torque	290 Nm @ (2400-2800rpm)
Cylinder configuration	Inline 4 cylinder
Swept volume	2.179 L
Bore x stroke	85mm x 96mm
Features	Variable geometry turbocharger (VGT), intercooler, cooled EGR
Fuel injection	Common rail direct injection with solenoid injectors

3. ENGINE INSTRUMENTATION AND DATA ACQUISITION

The reference engine was instrumented for high speed in-cylinder combustion and turbocharger diagnostics. For in-cylinder combustion diagnosis, the reference engine was instrumented with a flush mounted and front sealing Kistler 6052C piezo-electric pressure transducer. The sensor has been direct mounted on cylinder 1, which is the nearest cylinder to the front end of the crankshaft where a Kistler 2614CK angle encoder was mounted for accurate phasing of the acquired in-cylinder pressure traces[4] with 0.1-degree crank angle resolution. The acquired in-cylinder pressure traces were referenced using a Kistler 4007C high frequency piezo-resistive absolute pressure sensor flush mounted directly on the intake manifold, close to cylinder 1. For the measurement of exhaust manifold pressure, a Kistler 4075A water cooled piezo-resistive absolute pressure sensor was flush mounted on the exhaust manifold. The data from all these sensors were suitably amplified through dedicated amplifiers and sampled using Kistler KiBox high speed data acquisition and combustion analysis system.

The start and end of current pulse given to the solenoid-based fuel injectors were sensed using an inductance principle based Pico 60A current clamp. Rail pressure from the common rail was measured using the same piezo-resistive rail pressure sensor used on the reference engine. The current pulses given to inlet metering valve, EGR actuator and VGT actuator were measured using an in-house developed current probe working on hall-effect principle. The turbocharger was instrumented with Acam PicoturnSM-5.5 inductance principle based rotational speed sensor mounted directly on the compressor stator. The VGT position was monitored using an in-house developed sensor working on potentiometer principle. The data from the above-mentioned sensors were acquired using Kistler KiBox combustion analyser, as shown in Fig. 1.

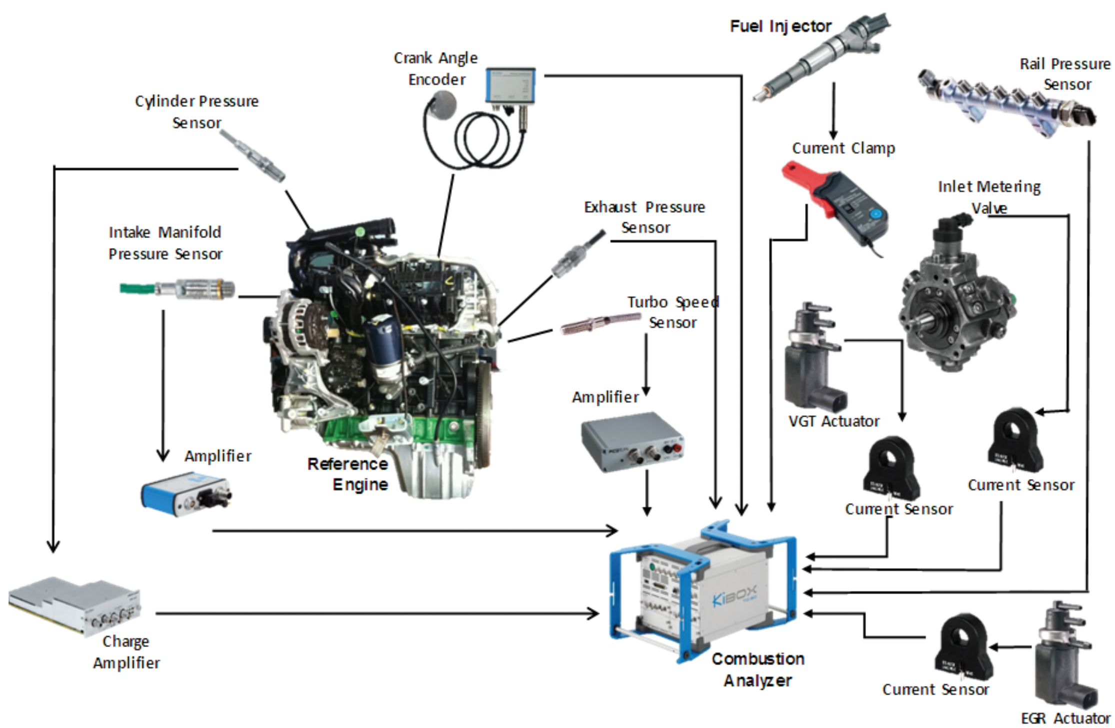

Figure 1. High speed data acquisition layout[5].

Slow analog signals like fuel flow rate, temperatures and pressures at different locations in combustion air path and fuel path were acquired using ETAS ES650 module in the steady state experimental setup and using the transient dynamometer's data acquisition modules on the transient setup. In addition, data from the On-Board Diagnostics (OBD) module of the stock ECU were also acquired using ETAS ES592 module through its CAN interface. A novel method of data synchronisation and data post-processing tool were also developed in-house for synchronised acquisition of data from the above mentioned hardware platforms during engine experiments[5].

4. EXPERIMENTAL SETUP

The reference engine was initially coupled to a steady state dynamometer for engine instrumentation and preliminary experiments with the stock ECU until the transient testing facility was setup. The fully instrumented engine was then moved to the transient testing facility where further experimentations and validations were completed.

4.1 Steady State Setup

The reference engine was coupled to an AVL alpha 160 eddy current dynamometer, as shown in Fig. 2. The dynamometer was controlled using AVL alpha controller. Fuel flow rate was measured using an AVL fuel flow meter working on the Coriolis principle and throttle position was set using an in-house developed throttle actuator. Engine coolant temperature and fuel temperature were controlled using liquid to water heat exchangers of shell and tube type. Boost temperature and oil temperature were regulated using convectional-type air blowers.

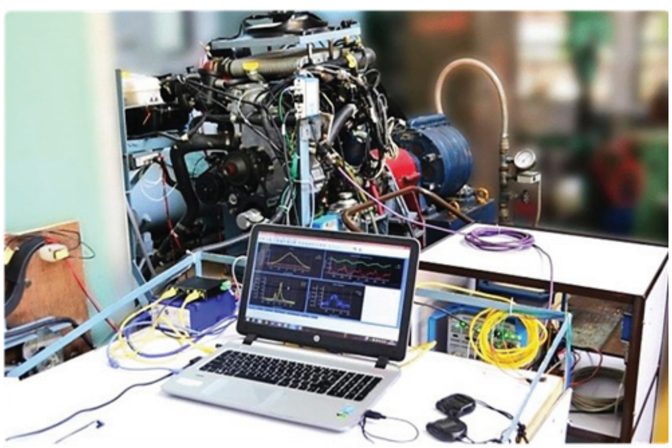

Figure 2. Steady state experimental set-up[5].

4.2 Transient Test Setup

A transient testing facility was setup for testing the reference engine with its controller under transient load and speed conditions. The test facility was procured from M/s Horiba India and setup as shown in Fig. 3. It consists of a low-inertia four quadrant operable air-cooled asynchronous AC machine which can load or motor the engine in both clockwise and anti-clockwise directions[6]. The system draws power from the grid when motoring the engine and supplies power to the grid when loading the engine. The system has sophisticated

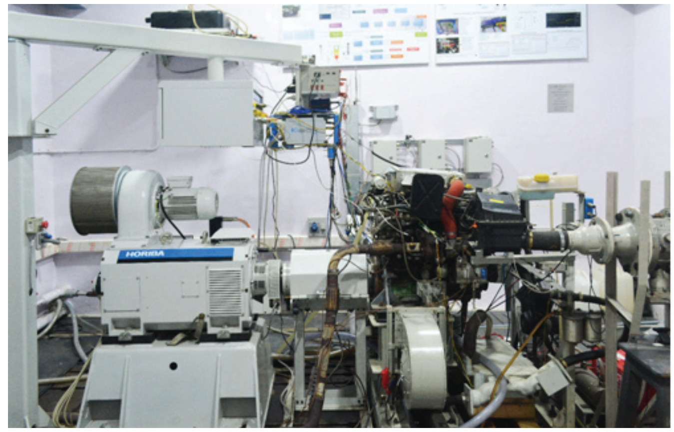

Figure 3. Transient engine-testing facility.

variable frequency drive to control the speed and load of the machine. The dynamometer controller, namely SPAARC can be remotely controlled from PC using STARS automation system which can also run automated engine test cycles and display and log the data acquired on the transient dynamometer.

A coolant-water heat exchanger was used to control the engine coolant temperature and an in-house developed air-water heat exchanger was used to control the intercooler outlet temperature at constant set values. The throttle position was set using a Horiba servo motor based throttle actuator while fuel consumption was measured using AVL 735S fuel mass flow meter working on the Coriolis principle. The fuel temperature was conditioned using Diesel-water tube-shell type heat exchanger. Air flow rate was measured using an Elster paddle wheel based air flow meter. Temperatures at various points along the air path were measured using K-type thermocouples. Static pressures at various points along the air path were measured using piezo-resistive pressure sensors. The above temperature and pressure data were acquired on Horiba Stars data acquisition system.

5. OPEN ENGINE CONTROLLER

An open engine controller hardware was required to implement the developed control strategies in the form of software codes[7]. FlexECU DI from M/s Etas India was identified as the most suited one for this work. It is a production 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 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. 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.

6. SOFTWARE ALGORITHM

The software architecture used for the control of the reference engine was as shown in Fig. 4. It consists of different closed-loop control modules for control of fuel rail pressure, boost pressure, low-idle speed governing and high idle-speed governing in addition to the EPM module, fuel injection module, and emergency shutdown module[8]. Fuel injection parameters such as number of injections per engine cycle, timing and duration of each injection pulse and PID tuning constants are set in open-loop by various calibratable one-dimensional and two-dimensional engine maps. The boost pressure and rail pressure controllers were designed to work at 1ms time-loops while all the other modules were designed to work in synchronisation with the engine position.

6.1 Rail Pressure Controller

Closed loop control of fuel rail pressure was realised using proportional integral derivative (PID) control[9-11]. The measured variable was the rail pressure while the controlled variable was the duty cycle of the inlet metering valve (IMV). The frequency of PWM signal fed to the IMV actuator was kept constant for all operating conditions. The schematic of the developed control logic is as shown in Fig. 5. The actual rail pressure was measured by connecting the rail pressure sensor to an analog input pin of the Flex-ECU. The desired rail pressure was pre-defined as a function of engine speed and throttle position. The difference between the desired rail pressure for the given speed and throttle positions and the measured rail pressure was given as an input to the PID block and based on the error, the PID block defines the duty cycle as an output. The duty cycle was clipped to ensure no negative values in case the rail pressure overshoots and also to avoid any abnormally high values in cases where the desired rail pressure cannot be reached. The clipped duty cycle was given as input to an emergency block, which overwrites the duty cycle to zero, thus turning off the control if the ECU senses any malfunction. The final duty cycle was used to generate a PWM signal which was the input to the actuator of the IMV.

6.2 Boost Pressure Controller

The boost pressure controller works in a very similar way to the fuel rail pressure controller[12-13]. The measured variable was the boost pressure measured at the outlet of the intercooler while the controlled variable was the duty cycle of the PWM signal given to the VGT actuator. The frequency of the PWM signal fed to the solenoid-based VGT actuator was kept constant for all operating conditions. The desired boost pressure was pre-defined as a function of engine speed and throttle position while the actual boost pressure was measured as an analog input from the boost pressure sensor. Based on the error, the controller sets the duty cycle of the VGT actuator.

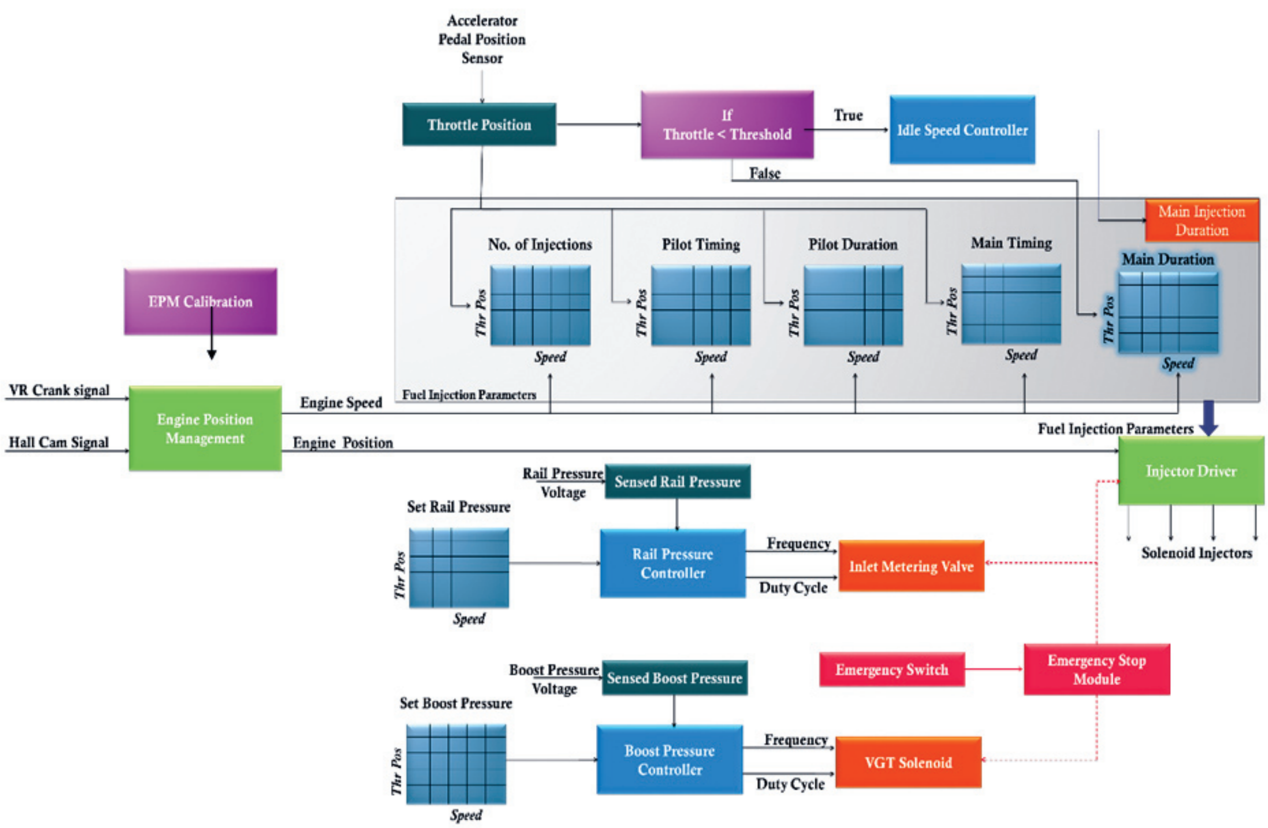

Figure 4. Basic control algorithm.

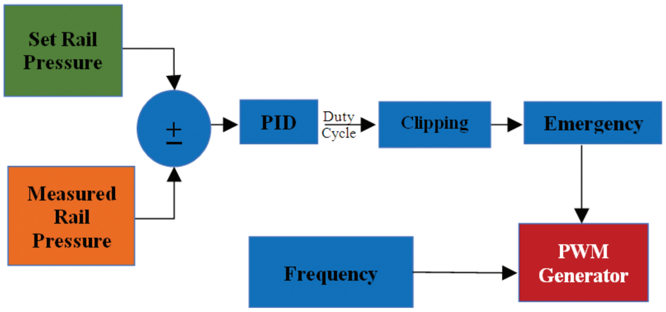

Figure 5. Fuel rail pressure control algorithm.

6.3 Low-Idle Speed Controller

Conventionally in common rail systems, idle speed is maintained using PID control[14-17]. Low-idle speed control logic was derived with main injection duration as the parameter controlled to set engine speed at the desired target value using PID control. The number of fuel injections per engine cycle, the timing of each injection pulse and the duration of each injection pulse were given from pre-defined calibratable maps. The closed loop control of low idle speed was coupled to the control of fuel rail pressure. During idling, the algorithm chooses the desired rail pressure for control based on the set engine speed. The logic inside the idle speed controller block is as shown in Fig. 6. The Measured Engine speed block receives the current engine speed from the EPM module. The difference between the current engine speed and set low-idle speed was given as input to the PID block. The clipping block sets a lower and upper limit to the output of the PID block. The lower limit ensures no misfire in any cylinder in any cycle. The higher limit ensures safe engine operation by avoiding high fuel injection quantities and its value is chosen based on the fuel quantity required during starting.

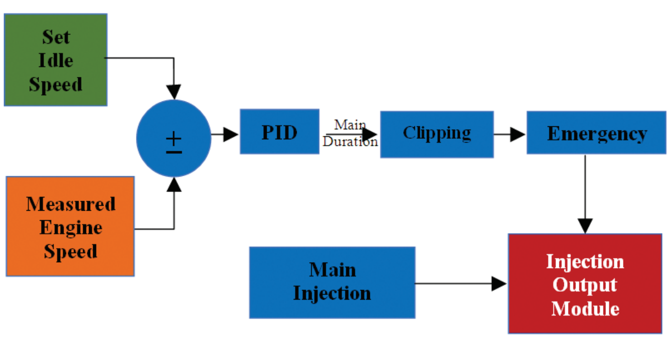

Figure 6. Low-Idle speed control algorithm.

7. TESTING AND TUNING OF CONTROLLER SOFTWARE

The controller software was developed and tested in systematic stages, before being taken to the actual engine test rig. The emergency shut-off module was one of the first modules to be incorporated in the algorithm and emergency shut-off switches were placed at suitable locations. This approach ensured safety of the hardware and test systems during the entire development phase.

7.1 EPM Calibration

The EPM module required to be calibrated before being taken to the reference engine. It was possible to test the EPM module by generating the speed signals using sophisticated devices such as function generators/FPGA based controllers[18-19]. But these signals still do not replicate the actual signals generated on the engine. Hence a dedicated setup was developed in-house to generate the cam and crank signals of an engine using the same sensors used on the reference engine. This consists of a representative toothed cam wheel and a 60-2 profiled crank wheel machined and mounted similar to that of the reference engine. The cam shaft was driven directly by a single-phase AC motor with the speed regulated by regulating the input voltage through a dimmer-stat while the crank wheel was driven at twice the speeds through a suitable toothed belt drive, thus avoiding any slippage. As in the reference engine, a hall-effect based position sensor was mounted to the cam wheel and a variable reluctance (VR) principle based position sensor was mounted to the crank wheel. The signals were interfaced to the open engine controller and the controller was suitably calibrated for proper synchronisation of the speed and position.

7.2 Rail Pressure Controller Calibration

It was important to test the developed rail pressure control module and test the fuel injectors for the precision of number of injections and timing and duration of each injection. A dedicated fuel injection test bench was built in-house with similar components as in the reference engine, as shown in Fig. 7. This consists of a high-pressure fuel pump with IMV driven by a three phase AC motor which was controlled using a 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 Nation Instruments controller (for safety). The common rail was also connected to solenoid fuel injectors and the set-up also generates speed signals as in the reference engine. The entire setup was interfaced to the open engine controller with in-house developed software and the rail pressure controller module was calibrated. Typical response of the rail pressure controller with a poorly tuned controller and a properly tuned controller is as shown in Fig. 8.

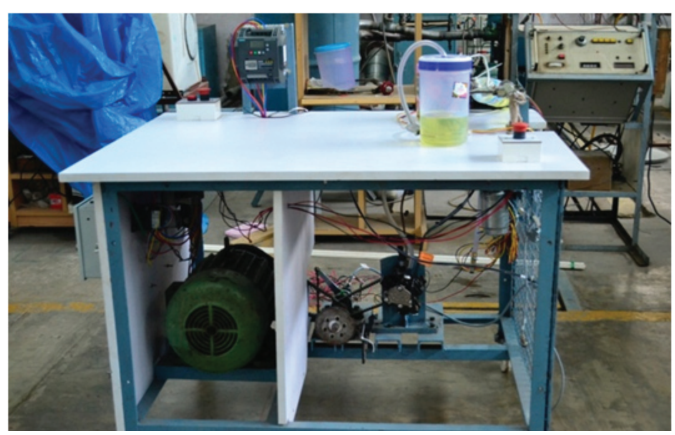

Figure 7. In-house developed fuel injection test rig.

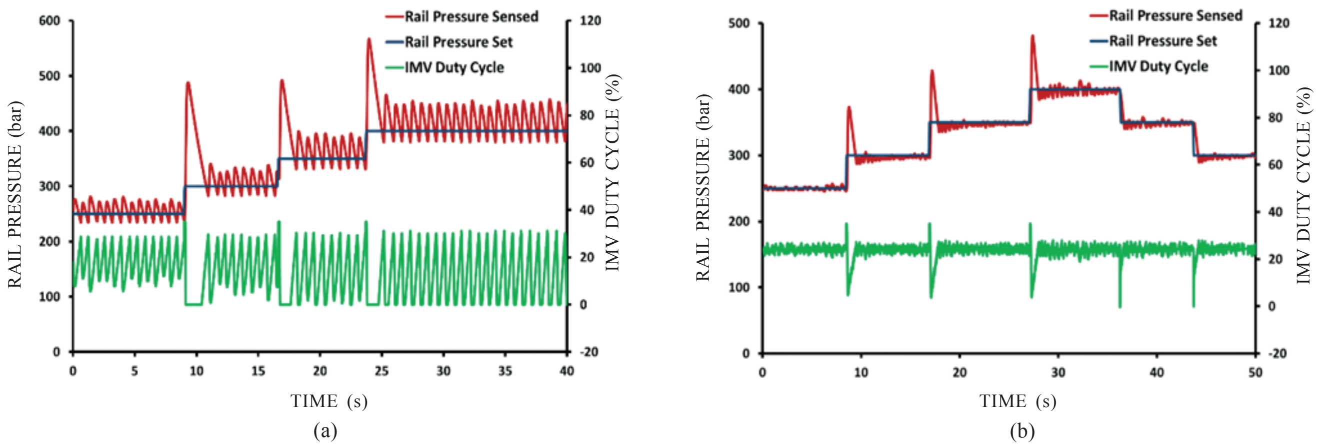

Figure 8. Fuel rail pressure controller tuning - response of a poorly tuned controller with Kp=0.5; Ki=0; Kd=0 as shown in (a) vs a well tuned controller with Kp=0.2; Ki=0.05; Kd=0 as shown in (b).

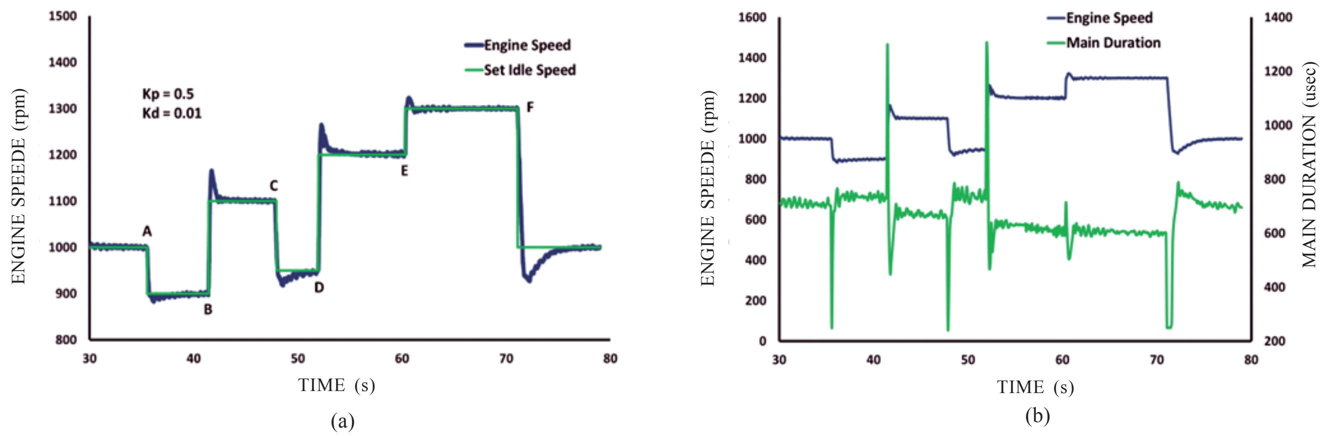

Figure 9. (a) Response of idle speed controller to changes in set idle speed and (b) Controller action taken against changes in set idle speed.

7.3 Low-idle Speed Controller Calibration

With the EPM and rail pressure controllers calibrated away from the engine, and since the effects of boost pressure are minimal during idling, it was possible to calibrate the idle speed controller online at the reference engine during its idling. The idle speed controller was first calibrated under steady state and then calibrated by dynamically changing the set idle speed using INCA. From Fig. 9, it can be observed that the idle speed governor maintains the idle speed by modulating the main injection pulse duration between a minimum and maximum value which can also be set by the user.

7.4 Boost Pressure Controller Calibration

With all other controller modules calibrated, it was possible to calibrate the boost pressure controller online at the reference engine[20]. The reference engine was taken to a speed and load where the effects of boost pressure are significant and the calibration was performed. Figure 10 shows a typical boost controller calibration activity at 1800 rpm and 40 per cent load. The boost pressure was observed to be 1.02 bar without any control. Then closed loop control of boost pressure was enabled and the following PID constants (Kp = 10, Ki = 10, Kd=0) were used as shown in Fig. 10.The boost pressure was

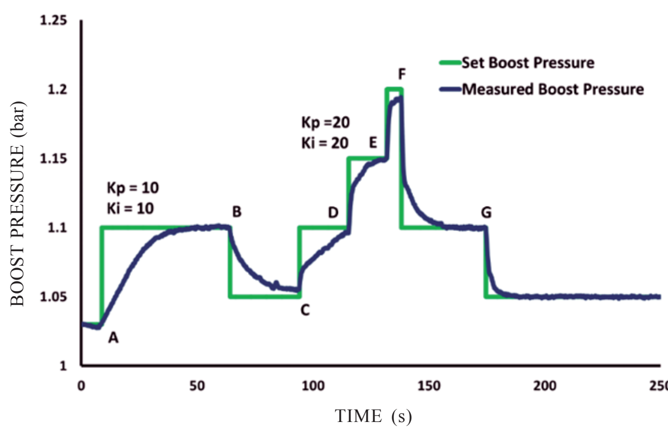

Figure 10. Typical boost controller calibration activity.

changed and by monitoring the response of the turbocharger, the optimum PID constants were obtained. As shown in Fig. 10, boost pressure was changed from 1.02 to 1.1 bar at A, 1.1 to 1.05 bar at B, 1.05 to 1.1 bar at C. It can be seen that, for all the three cases (A, B and C), the rise time of system was very high. Hence, the gains were increased to Kp = 20, Ki = 20, Kd=0. The boost pressure was then changed from 1.1 to 1.15

bar at D, 1.15 to 1.2 bar at E, 1.2 to 1.1 bar at F and 1.1 to 1.05 bar at G. It can be observed that the response of the system to the steps inputs at D, E, F and G was greatly improved.

8. VALIDATION OF CONTROL ALGORITHM USING TRANSIENT CYCLES

Based on field data collected from AFV engines, a representative transient cycle was established as shown in Fig. 11. The reference engine was subjected to the representative transient cycle and its response was monitored and validated[21]. The throttle position was set by the servo motor based throttle actuator and the engine speed was controlled by the dynamometer as specified in the reference transient cycle in Fig. 11 while the output torque was not controlled. It could be observed that the developed software algorithm performs satisfactorily under the subjective transient conditions. A representative result of the performance of the tuned rail pressure controller algorithm is shown in Fig. 12. The figure shows the desired values of rail pressure set by the developed engine control software during the transient cycle, the change in the control variable for rail pressure which is the duty cycle of the control pulse to the fuel inlet metering valve and the output of the control algorithm which is the rail pressure sensed by the rail pressure sensor. It could be observed that the tuned controller modules perform satisfactorily under the stipulated transient conditions.

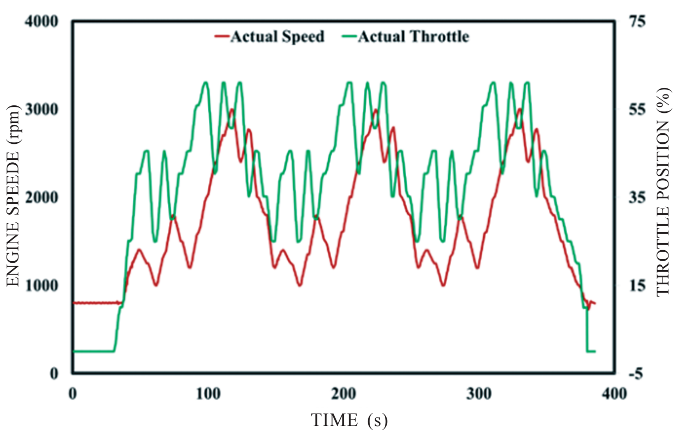

Figure 11. AFV field data based driving cycle

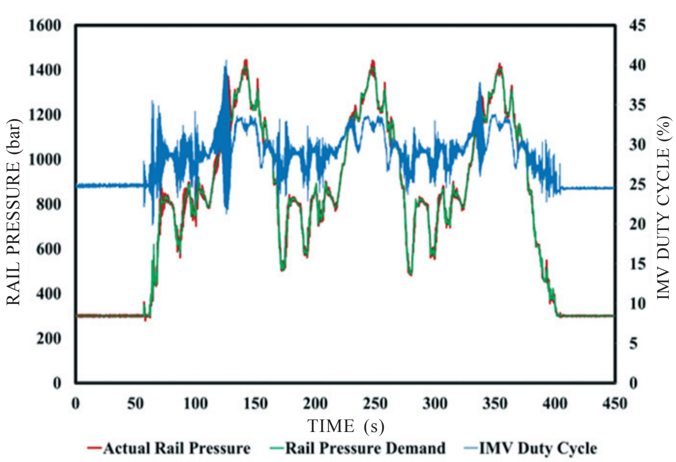

Figure 12. Performance of the rail pressure controller during transient cycle.

9. CONCLUSIONS

A complete control algorithm for a turbocharged, intercooled diesel engine was developed and incorporated on an open ECU. The software logic and data tables were tuned, tested and validated under military specific transient driving cycles on a specially developed transient test bed. The controller was found to work satisfactorily. A close control over different parameters like rail pressure, injection schedule, turbo boost pressure and speed was achieved. It is possible to incorporate additional military specific functions and diagnostic modules on the ECU.

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CONTRIBUTORS

Mr Jensen Samuel J., completed his Masters in Internal Combustion Engineering from College of Engineering Guindy, Anna University Chennai in 2011. Presently pursuing his PhD from Indian Institute of Technology Madras and working on modelling combustion for RT model-based control of Diesel engines during steady and transient operating conditions. Research interests include: IC engine testing, data acquisition, physics-based modelling and control.
Contribution in the current study, he has set-up the test facility and carried out the experimentation of the engine in the study.

Mr Paul Pramod M., 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 for the engine in the study.

Dr A. Ramesh, obtained his PhD (Internal combustion engines) from IIT Madras and post doctoral research work from Ecole Des Mines De Nantes, France. He is an Institute Chair Professor of Mechanical Engineering and also head of the Center for Continuing Education in IIT Madras. He has published over 135 research papers on GDI and HCCI engines, alternative fuels and engine management.
Contribution in the current study, he has arrived at the control logic 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.

Dr V. Ramanujachari started his career in DRDL, Hyderabad as Scientist 'B' in 1982 and worked on the Airbreathing Propulsion system for AKASH missile. Later, he taught at the Institute of Armament Technology, Pune. He was the Project Director of HSTDV project at DRDL, Hyderabad during 2009-2012. He was holding the position of Director, Research& Innovation Centre, IIT Madras Research Park, Chennai at the time of his retirement in 2016. His research interests are in the fields of combustion and propulsion.
Contribution in the current study, he has been instrumental in the initiation of this work and has reviewed this work periodically.

Mr Murugesan R, is a post graduate engineer and working as Scientist 'F' in Combat Vehicles R&D Establishment, DRDO. He has more than 28 years of experience and worked extensively in design and development of diesel engine and its sub-systems for armoured fighting vehicles and its evaluation. He is currently leading the Centre for Engineering Analysis Division (CEAD) in CVRDE.
Contribution in the current study, he has supported overall work and contributed to the generation of input data for the study.

Mr A. Kumarasamy, completed Masters from IITM, Chennai in 1995. Working as Scientist 'G' in CVRDE, Chennai and heading engine division. Developed compact cooling system for combat vehicles. Guided and upgraded power output of an existing engine and evaluated at field conditions. Presently guiding a team for developing engines for 400 – 1500 hp range. His research interests include diesel engine for Armoured Fighting Vehicles (AFVs) for 400 to 1500 hp range, compact cooling system for AFVs, efficient air filtration system for AFVs, advanced & efficient technologies for sub systems of diesel engine and its peripheral systems.
Contribution in the current study, he has initiated this study, reviewed the work and contributed to the integration of the cooling system of the engine under study.