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Research Article

Real Time Monitoring of Diesel Engine Injector Waveforms for Accurate Fuel Metering and Control

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This paper presents the development, experimentation, and validation of a reliable and robust system to monitor the injector pulse generated by an engine control module (ECM) which can easily be calibrated for different engine platforms and then feedback the corresponding fueling quantity to the real-time computer in a closed-loop controller in the loop (CIL) bench in order to achieve optimal fueling. This research utilizes field programmable gate arrays (FPGA) and direct memory access (DMA) transfer capability to achieve high speed data acquisition and delivery. This work is conducted in two stages: the first stage is to study the variability involved in the injected fueling quantity from pulse to pulse, from injector to injector, between real injector stators and inductor load cells, and over different operating conditions. Different thresholds have been used to find out the best start of injection (SOI) threshold and the end of injection (EOI) threshold that capture the injector "on-time" with best reliability and accuracy. Second stage involves development of a system that interprets the injector pulse into fueling quantity. The system can easily be calibrated for various platforms. Finally, the use of resulting correction table has been observed to capture the fueling quantity with highest accuracy.

1. Introduction

In order to further improve the fuel efficiency of a diesel engine, it is imperative to use optimal amount of fuel injection that will produce the demanded power while meeting the emission requirements. As such most diesel engine manufacturers, such as Cummins, Inc., use closed-loop test on a hardware-in-loop (HIL) bench which is a very important step in the performance testing of diesel engines. In order to carry out the systems' performance analysis, the model of the engine and all other components of the vehicle are run on a real-time computer that simulates the real vehicle. The ECM is fed with all the sensor signals it expects in a real vehicle, in real-time, from emulated sensors using required hardware. However, the real time model fails to run the closed loop real time simulation properly without the accurate information on fueling quantity being injected. The ECM calculates the desired fueling quantity with the control algorithm that takes into account all the required sensor feedbacks at each time step. Finally the injector "on-time", the amount of time the injector should inject the fuel into the cylinder, is looked up from a fuel on-time table, corresponding to the fueling quantity that is to be injected and the operating common-rail pressure. The corresponding electrical pulse is sent to the injector stators or the inductor load cells that emulates the injectors. This research investigates whether the inductors, instead of the injectors, are appropriate to be used in a closed loop bench if necessary correction measures can be taken to adopt this cheaper solution. It also investigates different thresholds in order to identify the one that works the best to capture the correct "on-time". The experimental results show that the double threshold scheme, with start of injection at 0.1 V and end of injection at 3 V, captures the on-time with the least amount of errors.

This work involves the use of FPGA-based data acquisition system having different threshold approaches with different FPGA configurations of circuitry. The FPGA hardware allows the usage of its prebuilt logic blocks and programmable routing resources to configure the silicon chips to implement custom hardware functionality [1] providing hardware-timed

speed and reliability. The real-time HIL simulation requires hardware-timed speed and reliability, which is the reason for selecting FPGA hardware. Reyneri et al. [2] presented their work with a complete HIL test bench for a common rail injection system where they demonstrated a codesign technique that integrated codesign and cosimulation of hardware (HW) and software (SW) which constituted the HIL bench. They used eight FPGA processors, one PC, one analog-to-digital (A/D), digital-to-analog (D/A) board and a data acquisition board, in the test bench, in addition to the common rail test bench and the cosimulation in CodeSimulink environment. Predefined voltage waveform computed on the basis of the required current waveform and the electrical model of the injector was sent to the injectors. Their work focused on testing the ECM performance, which requires the injected fueling quantity to be sensed and fedback to the software simulation running in the RT, which is different than the work we present her. The authors [2] used an ad-hoc hardware signal generator based on FPGA that powered the H bridges for the injectors. They used open-loop generation of current waveform. However, they tuned the inductor load cells, that is, R-L circuits with estimated R and L values. They employed neuro-fuzzy methodologies that characterized the injectors, that is, the electrical parameters, in order to tune the inductor load cells that allowed them to weight the fuel injected with cheaper load cells and still obtain desired precision. FPGA hardware and 8-channel A/D converter with about 20 kHz sample rate were used during the injector characterization process.

Saldaña-González et al. [3] presented-FPGA-based hardware implementation that takes the digitized voltage signals produced by the data acquisition electronics of the photomultiplier tubes and processes them to allow identifying events. The data was then used to determine the strength and positions of the interactions based on the logic of Anger to form a planar image that allows reconstruction of 2D image for medical diagnostics in a gamma camera in real time. Pozniak [4] presented the application of FPGA the based-multichannel, distributed, synchronous measurement systems for triggering, and data acquisition used in high-energy physics (HEP) experiments. Turqueti et al. [5] presented design and implementation of a 52 microphone MEMS array embedded in an FPGA platform with real-time processing capabilities.

The objective of this research is to investigate the variability and inaccuracy inherent in the injector monitoring process using various approaches and conclude the most cost effective and reasonably accurate system. The research investigates the variability involved in the fuel measurement system used for closing the loop between the plant models and the ECM on a CIL bench. We also investigate if the inductor load cells that emulate the injectors are adequate to be used in the CIL bench and how much tradeoff is needed to use the cheaper inductors instead of the injectors and if the inductor load cells or the injectors show certain offset that can be corrected on the benches through proper tuning. Another objective is to find how much variability is present from pulse to pulse, from injector to injector, and over different operating conditions. Finally, the system needs to be easily calibrateable to be used with different platforms. Therefore, a test sequence is needed to generate a correction table that will be able to capture the fueling quantity with best possible accuracy, within the limitation of hardware. This research also aims at reducing the latency in delivering data and improved robustness of the CIL system.

2. Experimental Setup

The performance of a diesel engine, both in terms of fuel efficiency and emission, is heavily dependent on the fuel system that delivers fuel into the engine cylinder, which takes care of precisely controlling the injection timing, correcting pressure of injection to ensure proper mixing of air and fuel taking into account proper fuel atomization, and other critical parameters. Cummins engines are controlled to ensure precise control of the fuel injection into the cylinder with the advanced fuel system that constitutes common-rail, pump, and high precision injectors. The necessity to reduce fuel consumption, exhaust gas emissions, and engine noise has led to advanced technologies being employed in the fuel systems, replacing the mechanical injection system.

In general, the common-rail architecture employs a common pressure accumulator or high pressure storage called rail. This rail is fed by a high pressure fuel pump that could be driven at crankshaft speed (engine or twice the camshaft speed). Sometimes high pressure radial pump, independently from the engine rate, generates high pressure at the rail. High pressure injection lines connect the common rail to the fuel injectors. ECM controls the pressure at the rail through inlet metering valve (IMV). The ECM generates the injection pulse, which controls the opening of the injectors with electromechanical actuators. The ECM calculates the fuel quantity needed based on a predefined characteristic curve, the engine model, the driver's intentions via the accelerator position, engine speed, torque, temperature, acceleration, and so forth. The electronic control facilitates flexibility in injection timing and metering control, reduced cycle-to-cycle and cylinder-to-cylinder variability, as well as, tighter control tolerances, and increased accuracy over very long periods of operations. Figure 1 shows the layout of the common-rail architecture of the fuel injection system [6].

The common rail system includes the following components (Figure 1):

(i) high pressure fuel pump,

(ii) rail for fuel storage and distribution,

(iii) injectors,

(iv) electronic control module (ECM).

The rail serves as a fuel accumulator to maintain a relatively constant pressure at all fueling rates used by the engine. The fuel volume in the rail also dampens pressure oscillations caused by the highpressure pump and the injection process. From the rail, the fuel is supplied at constant pressure to the injectors via high pressure pipes. The ECM generates current pulses which energize each injector solenoid valve in sequence and define the start and the end of each injection event per engine cycle. The common rail system can generate

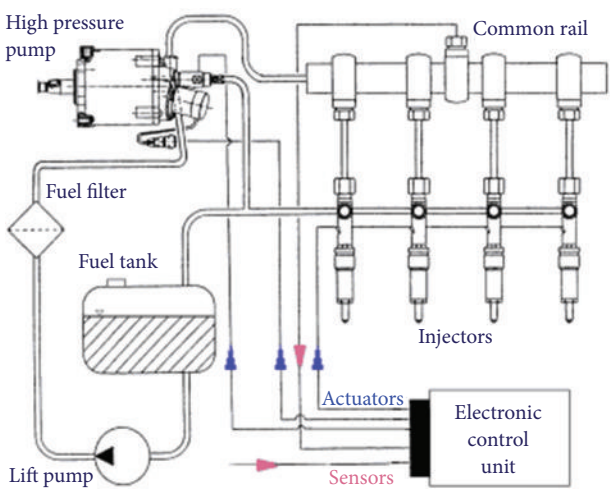

Figure 1: Schematic of the common-rail injection system.

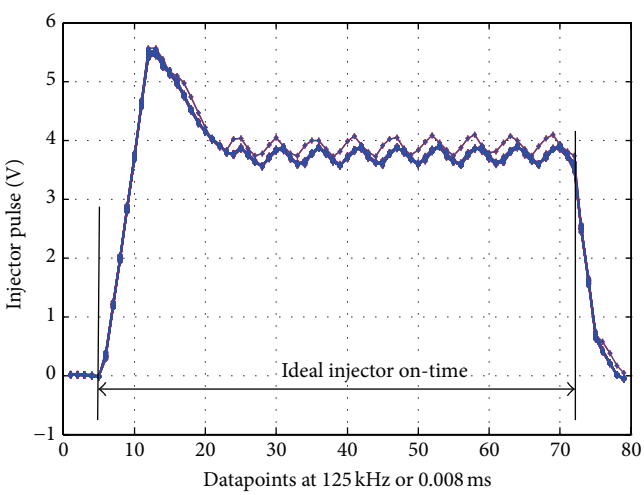

Figure 2: Injector pulse captured by the data acquisition system.

more than one injection per engine cycle and give more flexible control of the rate of injection compared to other injection system designs.

This research addresses the most important attribute of the fuel injection system, that is, metering of correct amount of fuel into the cylinder, in the application of HIL testing of the control algorithm. The control system is developed to calculate the correct amount of fuel to be injected by the fuel system in terms of fuel quantity, which is implemented by the fuel system by converting the fuel quantity into duration in time to inject the fuel at a given common-rail pressure. In order to carry out a hardware in the loop simulation, the simulation model needs the accurate measurement of the fuel being injected in order to carry out the accurate calculation to simulate the engine performance. The ECM generates the fueling signal in terms of electrical pulse to the injectors. The voltage waveform constitutes a high initial boost voltage to overcome the inertia of the injector mechanics, followed by a lower constant voltage which holds the injector nozzle to open position for the desired period of time. The hardware used in this research senses this electrical pulse and real time system that utilizes the FPGA personality and DMA transfer converts the pulse back into the fuel quantity. The electrical signal captured by the sensors does not distinctly indicate the start of injection and end of injection, which is the critical parameter to be figured out in this research, in order to calculate the most accurate measurement of injector on-time. The injector on-time, that is, the period of time the injector remains open to allow the fuel to be injected. The injection pulse captured is shown in Figure 2. Ideally, the injection on-time corresponds to the length of time between the time the injector signal starts to rise from zero value and the moment it starts to fall from the steady voltage value that is held during the injection period. Figure 2 clearly delineates the challenge involved in identifying the start of injection and end of injection.

The start of injection can be identified by the voltage value being over 0 V; however, the noise involved causes error in the identification. On the other hand, the steady value of voltage maintained at the time of injector being open is visibly noisy, and the approaches taken to identify the end of injection were to consider the slope of the voltage drop or identify a threshold value. The latter approach turned out to be more suitable, when coupled with identifying a threshold to distinguish the start of injection as well.

Another important parameter investigated in this research is the variability involved in the injector pulses captured by the proposed method. The importance of delivering the correct fuel quantity with consistency is very important in the hardware-in-the-loop test since the purpose of using simulation instead of real engine and hardware is largely the repeatability of tests, in addition to cost reduction. To determine the repeatability of the injection pulse monitoring system, standard deviation of the captured on-time was used as an indicator. The fuel quantity being injected by the ECM was overridden through the CAN bus, while capturing it by the system. The fuel quantity being identified is expected to be exactly the same as the value being overridden. However, the inherent variability was calculated by the standard deviation. In later stage of the research, injection on-time was directly overridden instead of the fuel quantity. The on-time was held at a steady value and the system logged the on-time captured by the proposed system. Different variability was obtained with different approaches of injection on-time capture.

The research aimed at identifying the optimal approach, in terms of cost of implementation, the accuracy, repeatability, and variability involved in capturing the correct fuel quantity being injected by the injector.

Analog input module NI-9205, along with Xilinx Virtex-5 Field Programmable Gate Arrays (FPGA) hardware and the direct memory access (DMA) transfer capability in the compact reconfigurable input-output (CRIO) real-time (RT) controller, has been utilized to capture the injector voltage signal generated by the ECM. Since the analog input module has a specification of ±10 V, and the peak voltage of the injector signal is 12 V, voltage dividers with 2 V : 1 V ratio were used to capture the signals. The analog signals were logged at

different data acquisition rates, and the voltage signals were postprocessed in MATLAB to obtain the on-time with various thresholding approaches in the first investigation phase. The shot-to-shot variability, that is, the variation of captured fueling quantity from pulse to pulse was compared with the standard deviation in different thresholding approaches, as well as different operating conditions. A different operating condition comprises different engine speed, common rail pressure, fueling quantity, and injector or inductor load cells on all six injectors or inductors. In the second phase, a real-time application, along with the FPGA bit-stream that imprinted the desired circuitry into the hardware, was built, compiled and deployed to the real-time target that could interpret the fueling quantity from the analog signals. The FPGA circuitry allowed the generation of engine speed signal (ESS) and engine position signal (EPS) to be generated to simulate the engine speed.

Since the injector signal generated by the ECM is of importance in this research, and the whole HIL bench for closed loop testing is not required, a separate bench was developed for this research to run tests through different static operating points of different variables in an open-loop testing environment. Figure 3 shows the schematic of the bench developed for this research. The windows host computer runs test sequence to go over different values of different variables under consideration. National Instrument's TestStand software was used to run the test sequence. At the beginning, the test sequence establishes a session through CUTY (a software interface) that allows the Windows host PC to communicate with the CAN communication. The Cummins software called Calterm was used to monitor the parameters being overridden on the CAN bus.

The electrical pulse generated by the ECM is passed through a load, either the real injector stators or the inductors that emulates the injectors in the CIL bench. In this research, the focus is to interpret the electrical signal generated by the ECM for the injector and provide the fueling quantity injected to the RT simulation. Therefore, the key issue of this research is to capture the injector pulse with highest accuracy at a reasonable cost. The research investigates if the system can continue to capture the correct fueling quantity if the ECM commands for fueling over a prolonged period of time. The analog injector signal could be converted in several ways; however, the research identified the simplest and most effective way to capture it. The fueling quantity injected or the injector "on-time" was overridden with the software CUTY and CAN bus. Therefore, the real-time computer used in this project was the National Instrument's Compact Reconfigurable Input Output (CRIO). The CRIO contains a real-time processor with a chassis, featuring built-in elemental I/O functions such as the FPGA read/write function that provides a communication interface to the highly optimized reconfigurable FPGA circuitry. The chassis contained one analog output module to generate the emulated common-rail pressure sensor signal, analog input module to capture the injector voltage signal, and digital output module to generate the EPS and ESS signals. Windows host PC communicates with the CRIO through ethernet connection. National Instruments TestStand and LabVIEW have been used to run the tests. Real-time applications were compiled, built, and deployed to the CRIO, including the FPGA bit files that imprinted the required FPGA personality. The automated test sequence on NI Teststand establishes connection with the ECM through the CAN bus, with the CUTY software for the ECM. CUTY is a Cummins proprietary software that has been used for accessing the values of the parameters on the CAN bus, as well as overriding the values of required parameters. The Teststand sequence overrides the value of the fueling quantity to be injected or the injector "on-time" through the data link. The sequence also communicates over the ethernet connection with the real-time application running on the CRIO to vary the simulated engine speed through network variables. The EPS/ESS signals corresponding to the simulated engine speed are generated by the FPGA personality, according to the crank angle of the engine. The ECM requires the common-rail pressure signal and the EPS/ESS signals in the corresponding pins to generate the injector signal. The common-rail pressure is varied over different values by the test sequence running on the NI Teststand on the host PC, through Ethernet connection to change the values in the real-time application running on the CRIO. The corresponding pressure sensor signal is generated by the analog output module, by emulating the sensor. Different test sequences were developed in different stages of the experimentation. The real-time application contained the FPGA personality that generated the desired EPS/ESS signal, corresponding to the engine speed; the RT application switched over different channels of the analog modules since the analog module had only one analog to digital converter, carrying out the DMA (direct memory access) transfer from the FPGA module to the memory of the RT computer. It created separate files for each state. "Different states" refers to different engine speeds, different common-rail pressures, different fueling quantities or the "on-time" that is overridden on the ECM, in case of injector stators or the inductors.

Figure 4 shows the injectors, the inductors, and the FPGA hardware. The research investigated if inductors are good enough for closed-loop testing, and it was found that they are not. Injector stators were used from production injectors of Cummins engines. The bench hardware made by Cummins provided the electrical protection and necessary systems to transform the line voltage to low as power DC voltage to supply electronic circuits and high power supply as well to drive the electrical injectors or load cells. The NI CRIO-9014 [7], along with NI 9111 chassis, having analog output, analog input, and digital I/O cards, is shown on the right side of the hardware in [8]. The NI 9205 [9] analog input module has been a key feature for in this research. The NI 9205 features are 32 single-ended or 16 differential analog inputs, 16-bit resolution, and a maximum sampling rate of 250 KS/s. Each channel has programmable input ranges of ±200 mV, ±1, ±5, and ±10 V. To protect against signal transients, the NI 9205 includes up to 60 V of overvoltage protection between input channels and common (COM). In addition, the NI 9205 also includes a channel-to-earth-ground double isolation barrier for safety, noise immunity, and high common-mode voltage range. The 4-slot CRIO-9111 [8] chassis has Xilinx Virtex-5 reconfigurable I/O FPGA core capable to automatically

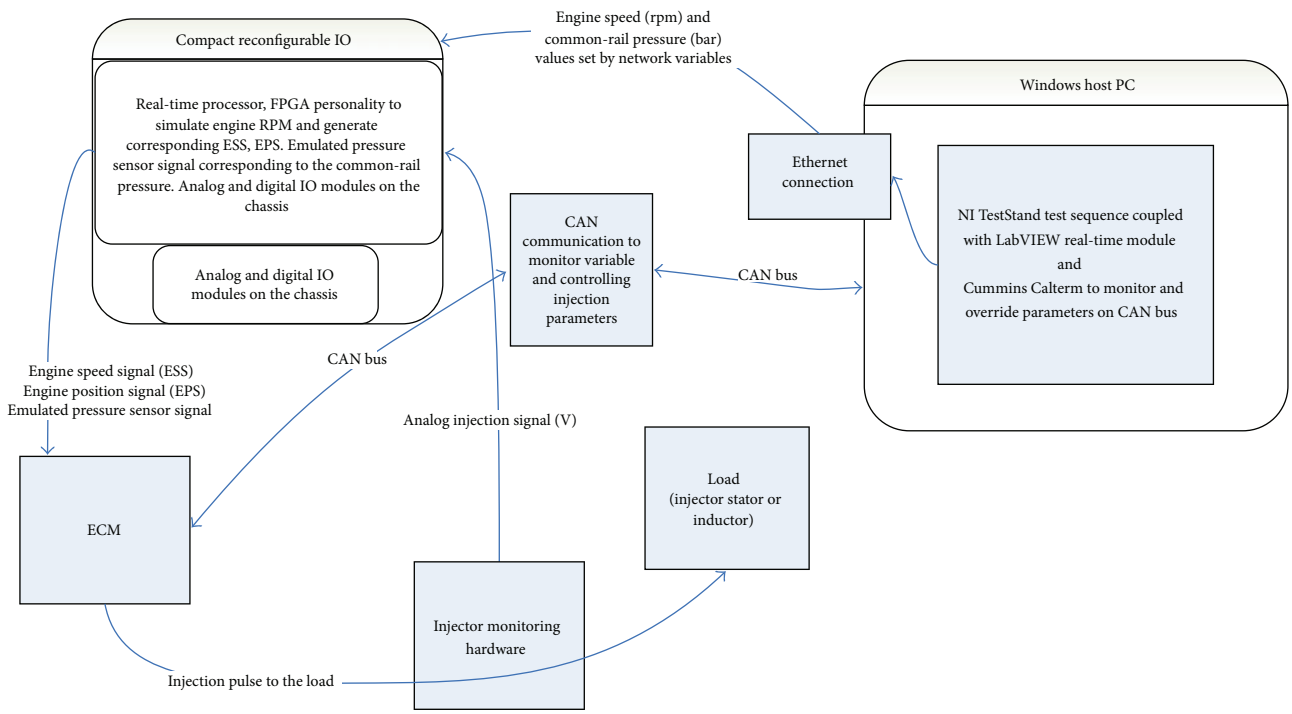

Figure 3: Layout of the bench for this research.

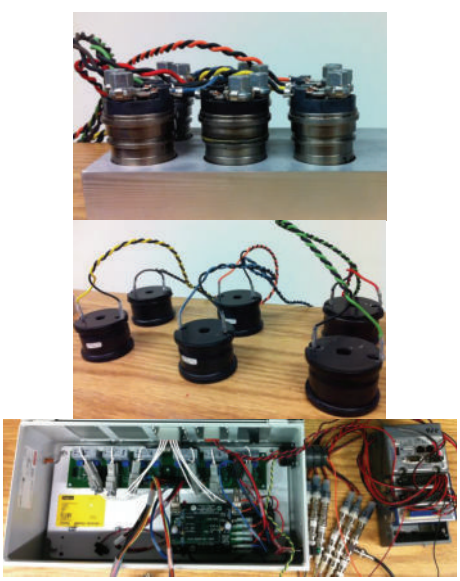

Figure 4: Injector stators used as load (top). Inductors that emulate real injectors as load (middle). FPGA hardware to capture the injection signal (bottom).

synthesize custom control and signal processing circuitry using LabVIEW. The research employed NI 9264 [10] analog output module to generate the pressure signal in order to emulate the pressure sensor. The ECM requires the pressure signal to calculate the injector on-time (ms) in order to inject certain amount of fuel. The research also utilized NI 9401 [11] 8 channel, 5 V/TTL high speed bidirectional digital I/O module to generate the engine position signal (EPS) and engine speed signal (ESS) to feed the ECM with the simulated engine speed. The test setup includes the six voltage dividers to accommodate the voltage provided by the hardware into the NI 9205 module [9]. Other hardware used in the bench were the inhouse power supply for the ECM and the electrical hardware, the Tektronix TDS 2024B oscilloscope, PEAK adapter to convert CAN messages and transfer into the computer, the CAN terminators to establish the CAN bus, and so forth.

This research employs a CRIO system offered by National Instruments. It contains an integrated real-time controller and a chassis, with a communication interface with a highly optimized reconfigurable FPGA circuitry, that contain slots for different modules used. National Instruments helps the users involved in the development of mechatronic control systems by providing hardware and software solutions in order to accelerate the development and testing of such systems. This supports creating real-time applications in LabVIEW, building and deploying the files into the RT system to implement real-time environment for any user-defined HIL Bench which falls into the targeted I/O criteria. The CRIO system used in this research is a real-time system for performing fast function prototyping. The CRIO-9014 runs the NI LabVIEW real-time module on the VxWorks real-time operating system (RTOS) for extreme reliability and determinism. With the CRIO-9014 real-time controller, one can use the leading VxWorks RTOS technology to quickly design, prototype, and deploy a customizable commercially available off-the-shelf (COTS) embedded system using LabVIEW graphical programming tools.

3. Experimental Results

The experimentation was carried out on the experimental bench to find the most cost effective, efficient, recalibratable, and reproducible solution to the injector monitoring problem with the following variable parameters under consideration:

(i) fuel quantity or injector on-time (ms),

(ii) engine speed,

(iii) common-rail pressure,

(iv) two different loads, that is, injectors or cost saving inductors to simulate injectors,

(v) six different injectors or inductors,

(vi) different thresholds.

In order to implement the injector monitoring system in the hardware-in-the-loop system, the system is required to maintain good accuracy in capturing the correct amount of fuel quantity over a large range of fueling, engine speed, and common-rail pressure with as little variation as possible. The research also investigates if the accuracy varies from injector to injector. Since the system, if satisfies requirements, is going to be implemented in a large number of hardware-in-the-loop benches, the cost of implementation is an important factor to consider as well.

The research begins with varying all the variables and consecutively ruling out some of the variations if found to have insignificant influence over the accuracy of the system. The data acquisition hardware available from NI had limitation in sampling rate. Therefore, initially only one NI-9205 module with 20.8 kHz sampling rate at each channel was considered to be used for all six channels.

To identify the start of injection and the end of injection, different thresholds were considered, narrowing down to the most effective approach. Initially, the end of injection was identified using the slope of injection pulse, which was not very successful due to the noise involved in the signal captured. Therefore, thresholds were used to identify the SOI and EOI, having only one threshold for both ends or two thresholds. The initial experiments show that the influence of varying common-rail pressure is comparatively insignificant. Therefore, the tests were carried out at varying engine speeds and fueling quantities with different threshold approaches on both kinds of loads. The sampling rate turned out to be the most significant factor in the accuracy of the system. Since the injector on-time remains the same with the constant fueling quantity over varying engine speed, it was expected to have the same accuracy. However, the experimental results show that the accuracy varies over different engine speeds.

Initially, tests showed that the accuracy of the system is not significantly dependent on common-rail pressure; therefore, tests were run at 1200 bar common-rail pressure over different engine speeds and fueling quantities for both injector stators and the inductors, six of them each. The injection pulses were logged in the form of discrete voltage values with 20.8 kHz sampling rate at each injector channels with a precision of 1 V, which was later increased to 0.0156 V precision value. The injection voltage values were logged in .tdms format. National Instrument's data analysis software DIAdem script was used to convert the .tdms files to .mat files in order to postprocess the data on MATLAB. The fueling "on-time" was extracted using various single thresholds or double thresholds in MATLAB. Single threshold approach uses same threshold value for both the start of injection (SOI) and end of injection (EOI). The SOI threshold is the value that determines when the injection has started; that is, as soon as the voltage value goes above the SOI threshold, the injection is considered to have started. Similarly, the EOI threshold is the value that determines when the injection has ended, that is, as soon as the voltage value goes below the EOI threshold, the injection is considered to have ended. In the first phase of the experiment, the double threshold approach considered EOI at the point where the voltage value starts to drop from a steady value; that is, instead of using a threshold to identify the EOI, the code considered five consecutive data points, and if the voltage value kept on falling through five points, the third point was considered the EOI point. The test sequence goes over different values of engine speeds and fueling quantities to be injected. The extracted pulse lengths are measured in milliseconds. The mean of all the pulse-lengths are calculated for each injector channel at each state, in both cases of injectors and inductors. The expected fueling "on-time" is the value overridden on the ECM. Therefore, the error in the fueling quantity was calculated at each of the states on the mean values using the following equation.

$$\text{error}\,(\%) = \frac{\text{ontime}_{\text{mean ontime}} - \text{ontime}_{\text{expected ontime}}}{\text{ontime}_{\text{expected ontime}}} \times 100. \tag{1}$$

Double threshold and single threshold at 2 V showed less variation from pulse to pulse; however, the variation is pronounced at 1500 rpm and 3000 rpm engine speeds. The mean of percentage errors at each state was calculated and plotted to compare the performance of the system with injectors or the inductors used as loads. Following plots show the comparison with different threshold approaches. Figures 5(a) and 5(b), and 6 show that the errors with inductors are lot more than the injectors. They signify the fact that, if cheaper solution, that is, inductors are used as the loads instead of using six production injectors for each bench, single threshold at 2 V is the best option. However, injectors show better results in double threshold approach. These experimental results pave way for further experimentation, to investigate the performance of the system with higher precision and higher sampling rate. These plots imparts us the knowledge, how much error can be expected, should we implement it. However, the error% is unacceptable for the CIL application since the CIL application requires higher accuracy at a fueling quantity as low as 10 mg/stk at a lower pressure lower than 1200 bar, which would certainly lead to a much more error.

It is evident from the previous experimental result that, using the highest sampling rate available with double threshold provide the best estimate of the calculated fueling quantity by the ECM; however, there is variability involved in the process. In order to implement this system in the HIL bench,

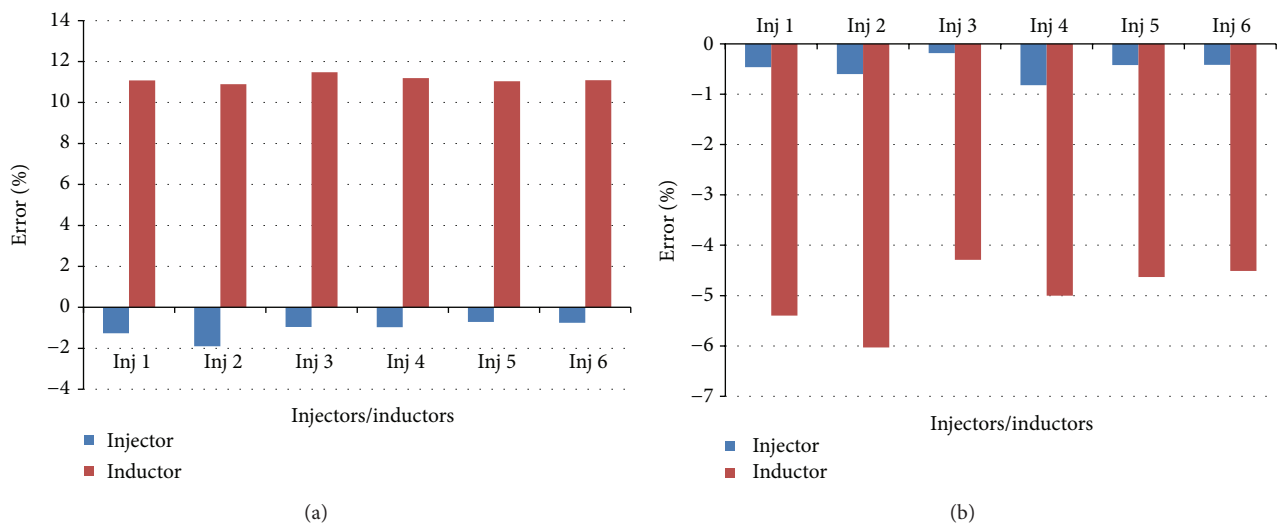

Figure 5: (a) Mean error (%) using single threshold at 0 V. (b) Mean error (%) using single threshold at 3 V.

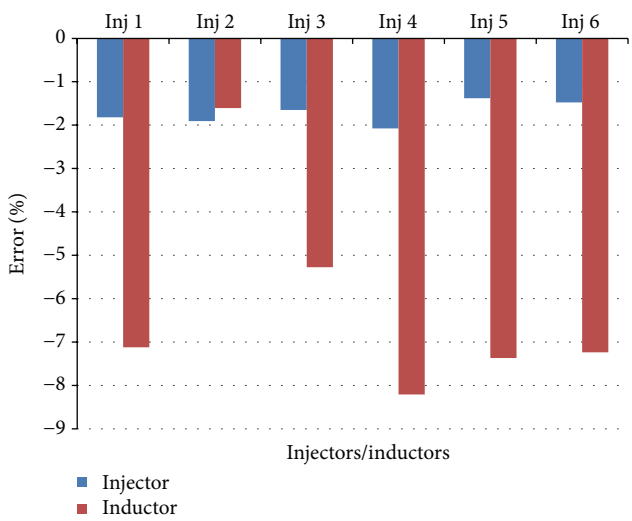

Figure 6: Mean error (%) using double threshold.

Table 1: DOE fixed factors and their levels.

Factors	Levels			
Engine speed (rpm)	750	1500	2250	
Pressure (bar)	600	1200	1800	
Fueling quantity (mg/stk)	10	50	100	150

it is critical to know the variability involved and the factors that contribute to the variability in order to have confidence in the system. And a correction model can be sought in future to make the system as accurate as possible over the entire operating range. Three fixed factors have been identified, that is, engine speed, common-rail pressure and fueling quantity at various levels in Table 1. Fifty replicates, that is, pulses were collected over randomized sequence of factor levels were collected using double threshold with SOI at 0.5 V and EOI at 2 V, with six injectors, as well as, six inductors.

The six injectors/inductors also showed variation in performance, however, the six injectors/inductors have been considered random factor, since they are expected to be identical and only the variability involved in the production process of the injectors contribute to the variability in the accuracy of the fueling quantity estimated by the system.

A full factorial design of experiment (DOE) was carried out with randomized run order of the fixed factors both on injectors and inductors, having the error percentage in the estimation of the fueling quantity being the response variable. The DOE result with 95% confidence interval showed that, all the fixed factors and interactions were contributing to the rejection of the null hypothesis that, the data collected over all the levels of all the factors represent the natural variability of only one process. The mathematical model of this experiment that uses three way analysis of variance (ANOVA) and design is,

$$E = \mu + S_i + P_j + F_k + SP_{ij} + SF_{ik} + PF_{jk} + SPF_{ijk} + \varepsilon_{m(ijk)}, \quad (2)$$

where S is the engine speed, P is the common-rail pressure, F is the fueling quantity, i, j, k are 1 through 50, and $m = 1, 2, 3, 4$.

Six injectors and six inductors were used in this research and it has been found that, the variability of error is similar. However, the mean error percents are much higher with inductors than with real production injectors as load on the HIL bench. Figure 7 shows that, the error percent is distinctly higher with inductors than with the injectors, however, the consistency of the error with both the injectors and inductors points out the fact that, the error can be corrected with regression algorithm.

Figure 8 shows that the difference in mean error percents is significant between injectors and inductors and the error varies over a larger range in response to the common-rail pressure with inductors than the injectors.

Figure 9 shows the large influence of fueling quantity on the mean of error percents with inductors as opposed to

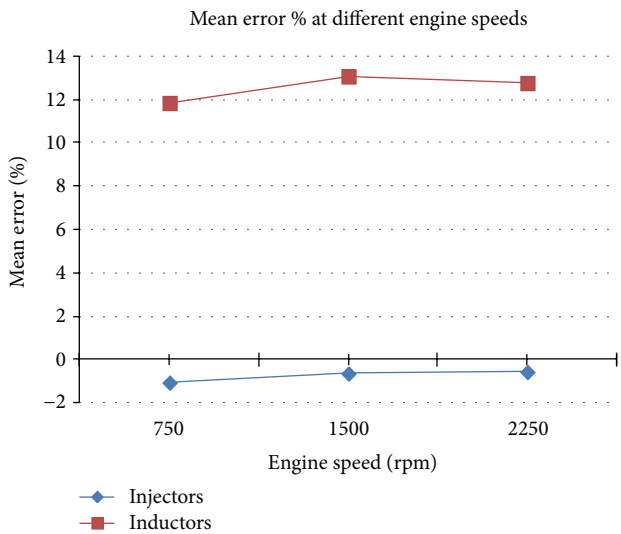

Figure 7: Comparing error % against engine speed for injectors and inductors.

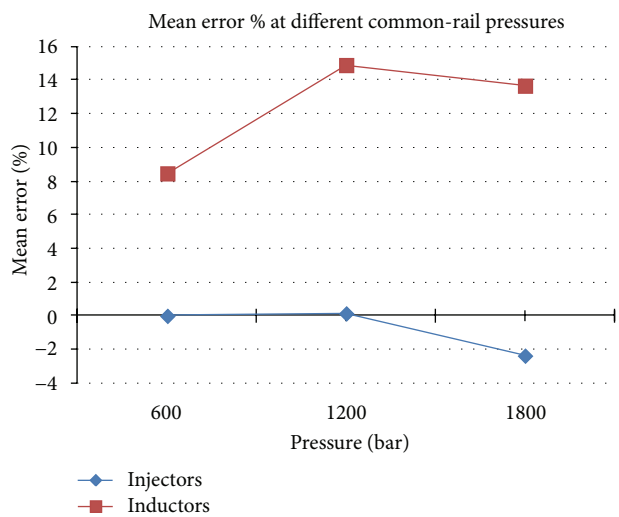

Figure 8: Comparing error % against bar pressure for injectors and inductors.

injectors. However, the mean error shows a consistent trend that can be corrected with a regression algorithm

Previous analysis of variability showed that the variability of standard deviation of error percent with injectors at different engine speeds is significantly (95% statistical confidence) different from the variability of the whole process of variability, considering the fixed factors. However, incorporating the six injectors and carrying out mixed model ANOVA exposed the fact that the interaction of engine speed and fueling add significantly different variability distribution compared to the normally distributed variability of the whole process of standard deviation. It signifies that, if the engine speed and fueling do not vary, the standard deviation of error maintains the same distribution around the mean standard deviations of error percent. Interaction of engine speed and fueling generates statistically significant different distribution

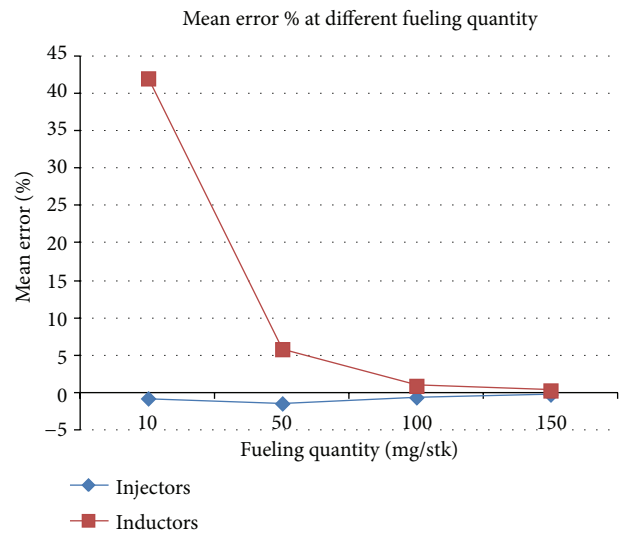

Figure 9: Comparing error % against fueling quantity for injectors and inductors.

of standard deviation of error percent; that is, varying pressure or using different injectors does not contribute to the variability of the standard deviation of error percent. On the other hand, the inductors with only the fixed factor model shows that all the fixed factors fall under the same normal distribution of standard deviation of error percent. However, when the mixed model of ANOVA was carried out, it pointed out that, the interaction of engine speed with all other three factors, that is, pressure, fueling quantity and inductor number add different distribution that is statistically significant. Therefore, the system's variability depends on all the variable factors, including different inductors. The standard deviation of all the values of standard deviations of error percent with injectors in logarithmic scale is 3.48534, while with inductors, the standard deviations of all the values of standard deviations of error percent in logarithmic scale is 3.14255.

The research involved development of a bench setup that is capable to test injector performance for fueling quantity monitoring, with automated test sequence that goes over all the predefined steady state operating points, using custom steps in NI Teststand to establish communication through CUTY and CAN bus to override parameter values on ECM, as well as monitoring the CAN bus to make sure that the correct values are being registered by the ECM from the emulated sensors. The bench uses FPGA personality to model the engine crank shaft rotation by generating high speed EPS/ESS signal, in addition to pressure sensor signal. The bench is capable to monitor the analog injector pulse, use double thresholds to capture the fueling on-time, and feed the engine model running on real-time computer with the correct values of fueling quantity through high speed DMA transfer using FIFO method. Future research can be carried out on this bench with different types of injectors, such as, injectors using piezoelectric technology, without using the expensive resource, that is, the fully capable closed loop test development bench. The research shows the high amount

of error that persists if single AI module is used for more than one injector monitoring. There are certain regions of operation with low error, therefore, the cheaper solution can be selected for an application that does not operate in high error region or in cases when the tests carried out are not susceptible to this high error. Statistical analysis was carried out on the system that uses one module allowing data acquisition at 125 kHz on each injector with differential input, which is the most expensive solution to implement on the closed loop HIL test bench. The research also compares the performance of the system with the production injector and the inductors load cells that emulates the injectors. The statistical analysis shows that, the expensive injectors can be replaced by inductor load cells if an error correction algorithm is incorporated into the system, since it showed about 40% error at lower fueling quantity, which may potentially cause unstable solution of the idle state of engine simulation on the bench. On the other hand, the injectors perform with very low error percent, that is, −2.38045% to 0.13551% error with less than 4% standard deviations, unless the system is used at an engine speed as high 2250 rpm. The mixed model ANOVA, which is a relatively new technique to carry out multivariate ANOVA exposed the fact that, the variability of the error percent varies with 95% statistical confidence, over different interaction values of engine speed and fueling quantity when the production quality injectors are used, while the value varies with the impact on all four variables, that is, engine speed, fueling quantity, pressure, and different inductors.

4. Conclusion

Based on the experimental data, it can be concluded that the injector loads are a better choice for the HIL bench to realistically emulate the injector waveforms. This analysis also shows that the variability of the error percent is not influenced by the common-rail pressure or different injectors, which is not the case with inductors. However, the variability is not very different with injectors or inductors in terms of standard deviation of error percent; that is, if the variability range is acceptable for a particular HIL test application, the inductors can be used, provided that the error correction algorithm is incorporated into the system. The proposed system was found to be capable of reducing the latency in the delivery of fueling quantity in closed loop HIL tests on the current benches that utilize CAN message instead. Additionally, the double thresholding approach was found to yield better accuracy and lower variability in capturing the correct fueling quantity. Finally, in order to take the inherent offset in the system into account, a test sequence was developed to generate a fueling correction table for a particular platform that shows a better result in estimating the fueling quantity.

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