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KNOCK DETECTION AND CONTROL ALGORITHM OF DIESEL-DUAL-FUEL ENGINE USING PRACTICAL MULTIVARIABLE CONTROL

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ABSTRACT

The detection and reduction of Diesel-Dual-Fuel engine knock is the important function of powertrain control to ensure engine longevity. In this paper, appropriate knock detection system of DDF engines, based on a Motorola ProSAK IC, was implemented. The electronic control unit (ECU) received high-frequency vibration signal from a piezo-electric knock sensor. The knock detection algorithm modified raw signal into knock intensity which use for monitoring the knock occurrence. The controller adjusted control variables simultaneously in order to reduce the unpredictable engine knock. Those variables are diesel injection timing, diesel quantity and natural gas quantity. 2KD-FTV engine on a Toyota Hilux Vigo were converted for dual fuel mode. Experimental results from road tests showed that engine knock was reduced by the control scheme especially during transient operation.

Keywords: Engine Knock Control, DDF Engine, ECU, Natural Gas

INTRODUCTION

Diesel-Dual-Fuel (DDF) engines are modified diesel engines which use CNG or LPG as alternative fuel. In the DDF engines, natural gas as a main fuel is injected in the intake ports of each cylinder. Small amount of diesel is used as pilot fuel which acts as “liquid” spark plug. Both fuels influence the combustion processes which are very sensitive to cyclical fluctuations in the thermodynamic state. Uncertainty of the engine operation causes engine knock which is undesirable phenomenon.

The previous research results showed that obtaining energy from natural gas 60-90 percent is possible. Data was based on engine operation as well as engine specification. However, when engine operates on high gas ratio, engine produce high emissions such as hydro-carbon (HC), nitrogen oxide (NO_x) and particle matter (PM). There is a trade-off between emissions, engine efficiency and gas ratio which they have to be optimized during engine calibration processes. By some regions where early diesel pilot injection was adopted, combustion mode is switched from the conventional to the advanced such as PCCI (Leermakers et al., 2011). Combustion is unstable and may cause engine knock.

SI knock is found in dedicated engines. SI knock refers to the spontaneous combustion of in-cylinder end gases (Brecq & Le Corre, 2005). End gases are un-burnt premixed fuel and air in front of the flame front. The knock sometime called self-ignition combustion which is a function of temperature, pressure and time. While CI engine knock refers to the combustion with prolonged ignition delay period. Engine knock causes shock waves and high in-cylinder peak pressure. Engine knock may lead to permanent damage of piston crown, cylinder wall and cylinder head (SatyanarayanaMurthy, 2011). CI knock, SI knock, HCCI knock and hard combustion are found in DDF engines (Dec, 2009). The factors affecting on knock characteristic of DDF engines have been included ignition delay, pilot quantity, engine load and speed, turbulence and gas flow rate (Nwafor, 2002).

Engine knock is observed from in-cylinder pressure rise rate (PRR), ionization current feedback, and vibration signal. The pressure sensor has been widely used during off-line engine calibration, for example, Delco Electronics Knock Analysis Instrument (KAI) (Wagner et al., 1998). The pressure sensors and ionization sensors are noble indicators but not practical due to the high cost (Zhu et al., 2007). Vibration sensors are the best choice for on-line knock control at present. A vibration sensor was applied to a diesel HCCI engine to reduce engine knock (Grondin et al., 2008).

Various knock control algorithms were found in the following textbooks; (Stotsky, 2009) and (Kiencke & Nielsen, 2005). In event-based knock control, when knock intensity is above a threshold, fixed corrective action is applied to prevent knock event. Lezius et al. (2008) defined “distance to knock limit” relating to knock threshold. They adjusted ignition timing of SI engine correlate with maximum of derivation of in-cylinder pressure. The ignition angle is controlled close to knock limit. Peyton Jones et al. (2013) presented an alternative stochastic control algorithm of engine knock based on probability density function of knock intensity. With likelihood-based stochastic knock controller, SI engine operated close to knock limit while also maintained a rapid transient response. Yaovaja & Chatlatanagulchai (2014) implemented a fuzzy supervisory system for knock control of a DDF engine. The engine was performed on the test bed to run on NEDC test. The controller regulated knock at appropriate intensity value and the engine emitted less NO_x.

This paper studied on the knock detection and control of a DDF engine by using a practical control system. Knock detection system and the control algorithm were deployed into a production Electronic Control Unit (ECU). Diesel injection timings and durations as well as gas quantity were the main control variables. In order to control engine knock, adjusting those variables simultaneously should give good results and higher stability.

METHODS

In this paper, Toyota 2KD-FTV diesel engine on a Toyota Hilux Vigo was converted for dual fuel mode. The OEM diesel engine specifications are depicted in the Table 1. The modified DDF engine is shown in Figure 1. The type-I CNG cylinders and gas injection system were installed on the truck. The high pressure of gas is reduced to 40 Psi. Four gas injectors were installed at intake ports and the back of the intake valves of each cylinder.

The 128-pin ECU is shown in Figure2. The engine mapping was modified from the Toyota OEM ECU by using OBD-II information. In our DDF engine, first start of diesel injection timing (SOI) is pilot SOI (before Top Dead Center, dbTDC). The second SOI is main SOI. End of injection (EOI) of natural gas is fixed at 240 dbTDC. Injection durations were controlled corresponding to fuel quantity demand and fuel pressure at that moment. Diesel split ratio is a fraction of diesel pilot mass over total diesel mass. Gas ratio is a fraction of energy by CNG over total fuel energy.

Figure 1 (left) Toyota Hilux Vigo and (right) Diesel-Dual-Fuel engine

Table 1 Engine specifications

Item	Detail
Engine Model	Toyota 2KD-FTV, Diesel engine
Engine Type	4 Cylinders (Inline), 16 Valves (DOHC), Turbocharger
Fuel System	Common-rail direct injection, Firing order 1-3-4-2
Physical Details	Displacement 2,494 cc / Compression ratio 18.51
	Bore 92.0 mm/ Stroke 93.8 mm/ Connecting rod 158.5 mm
Max Power/ Torque	75 kW at 3,600 rpm/ 260 Nm at 1,600
Valve Timings	IVO 718 deg / IVC 211 deg / EVO 510 deg / EVC 0 deg

The Bosch KS-P knock sensor and piezoelectric vibration sensor are shown in Figure 2. This sensor is used for detecting structural born vibrations in the frequency range of 1-20 kHz due to uncontrolled combustion. The sensitivity is 26±8 mV/g at 5 kHz (Woodward Inc., 2017).

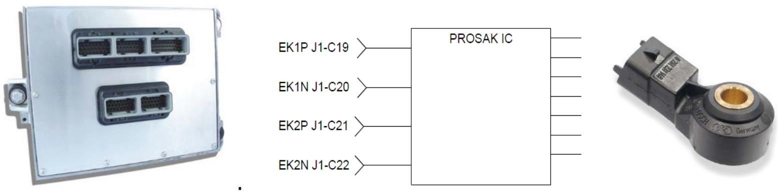

Figure 2 (left) 128-pin ECU (center) ProSAK IC (right) Bosch KS-P knock sensor

Source: Woodward Inc. (2017)

Analog signal from the knock sensor was acquired to Motorola ProSAK IC, integrated in the 128-pin ECU, with fast data sampling rate at 145.8 kHz. The proposed knock detection method with the ProSAK has five-step sequential procedure as shown in Figure 3. Raw analog knock was used to determine knock intensity which describes knock occurrence and violence.

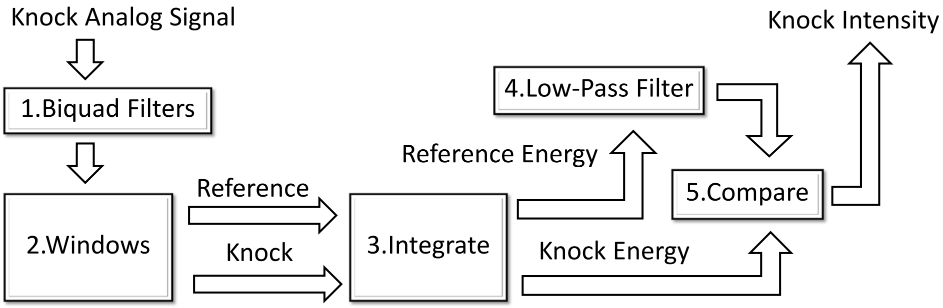

Figure 3 Knock Detection Method

Motorola ProSAK has 8th-order programmable digital IIR filter. It is implemented as a cascade of four digital biquad filters as shown in the equation 1. Digital biquad filter is a second-order recursive linear filter; containing two poles and two zeros. The first step is designing a band-pass Butterworth filter and converting to a set of Biquad filter coefficients.

$$H(z)=\frac{b_{0A}+b_{1A}z^{-1}+b_{2A}z^{-2}}{1+a_{1A}z^{-1}+a_{2A}z^{-2}}+\frac{b_{0B}+b_{1B}z^{-1}+b_{2B}z^{-2}}{1+a_{1B}z^{-1}+a_{2B}z^{-2}}+\frac{b_{0C}+b_{1C}z^{-1}+b_{2C}z^{-2}}{1+a_{1C}z^{-1}+a_{2C}z^{-2}}+\frac{b_{0D}+b_{1D}z^{-1}+b_{2D}z^{-2}}{1+a_{1D}z^{-1}+a_{2D}z^{-2}} \quad (1)$$

Second step, appropriated knock window must be chosen equivalent to the crank angle range of combustion event. The window should capture the maximum knocking energy. Reference window, which is non-combustion range, is selected to capture engine-noise energy. Third, “Knock Energy” is the integral value of knock signal over the knock window, while “Reference Energy” is the integral value of knock signal over the reference window. Forth, first-order filtering is applied on the reference energy in order to smooth engine-noise energy. Knock intensity is calculated by comparing the knock energy and smooth reference energy. As a result, knock intensity primarily changes due to activity in the knock window. In DDF engine, several control parameters affect engine knock. From our engine calibration experiences, the techniques to reduce DDF engine knock during early pilot injection are listed in Table 2. Three main parameters were chosen for multi-variable feedback control.

Table 2 Parameters that affect DDF engine knock during early pilot injection

Parameters	How To Reduce Engine Knock
Diesel pilot SOI*	Advance (increase SOI, dbTDC)
Diesel Split Ratio*	Decrease (use less pilot injection)
Gas Ratio*	Increase (increase CNG)
Rail Pressure	Decrease (use less injection pressure, MPa)
Throttle	Increase (increase fresh air, %)
EGR Valve	Decrease (increase fresh air, %)

* Parameters selected for the control loop

In Figure 4 showed the knock control system diagram of this paper. Knock intensity from cylinder#2, which is close to the sensor position, is a negative feedback for the control loop. Set-point, called knock threshold, is calculated from a fixed-map which inputs are engine speed (N) and engine load (τ). Calibrated Diesel pilot SOI (a_{i1}), as a function of N and τ inputs, is added to knock control input (a_{k1}). The summation is actuator set-point command (a_{e1}). There is a hysteresis function to determine engine knock occurrence with the lower and upper of 550 and 500. With engine knock, reduce knock control parameter (Δa_{b1}) is added to a_{k1}. But without engine knock, drain knock control parameter (Δa_{s1}) is subtracted from a_{k1} in order to reverse value back to the original map. Range of the a_{k1} adjustment is 0-12 dbTDC. Discrete equation of the control system was written as equation 2.

Similar to the pilot SOI control loop, calibrated diesel split ratio (a_{i2}) is adjusted with the control input (a_{k2}) and calibrated gas ratio (a_{i3}) is adjusted with the control input (a_{k3}). Furthermore, the conditional criterions are taking into account for these parameters. Diesel split ratio is reduced only when first injection is primary fuel. Natural gas should not be too high for this operation. Output saturations are also implemented to diesel split ratio and gas ratio. The engine control parameters are depicted in Table 3.

$$\begin{bmatrix} a_{e1}(n) \\ a_{e2}(n) \\ a_{e3}(n) \end{bmatrix} = \begin{bmatrix} a_{i1}(n) \\ a_{i2}(n) \\ a_{i3}(n) \end{bmatrix} + \begin{bmatrix} a_{k1}(n-1) \\ a_{k2}(n-1) \\ a_{k3}(n-1) \end{bmatrix} - \begin{bmatrix} \Delta a_{b1} \\ \Delta a_{b2} \\ \Delta a_{b3} \end{bmatrix} + \begin{bmatrix} \Delta a_{s1} \\ \Delta a_{s2} \\ \Delta a_{s3} \end{bmatrix} \quad (2)$$

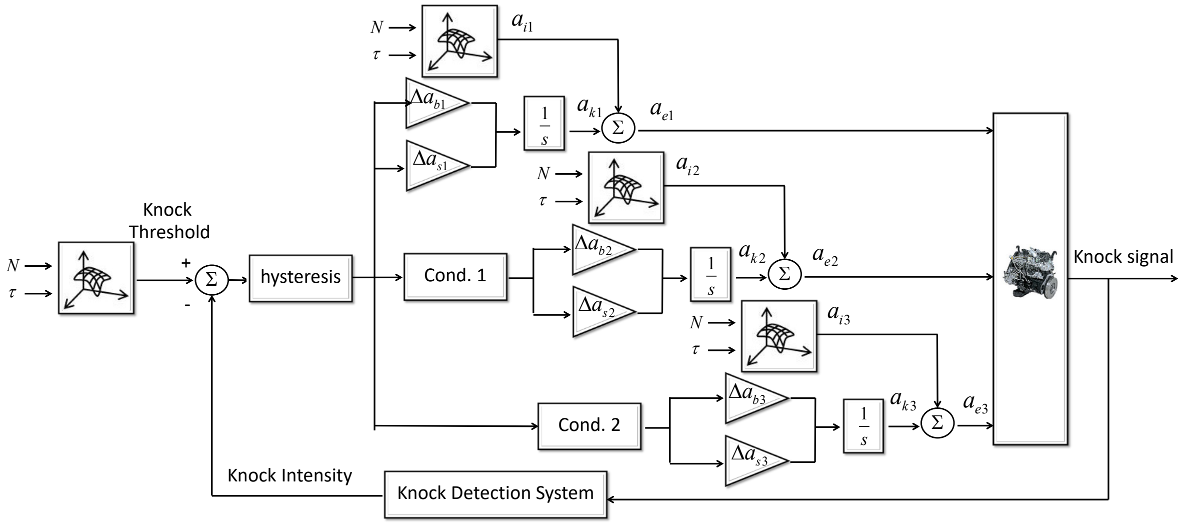

Figure 4 Multivariable knock feedback control algorithm

RESULTS AND DISCUSSIONS

Experiments were performed on our DDF engine to show knock detection (identification) performance and knock control performance. During knock detection tests, the engine speed is fixed at 2,000 rpm and the engine load is fixed at 20 percent. Diesel main injection is set to 6.2 mg/stroke and no diesel pilot fueling. Those diesel fuel quantities are manually switched to 4.2 and 2.8 mg/stroke, respectively, in order to simulate engine knock. Engine audible noise was noticeable, in-cylinder pressure was fluctuated and high PRR was found at this condition. Only one engine knock sensor is attached, but the acquired signal was used for generating knock intensity for each cylinder corresponding to engine crank angle.

In order to find out the appropriate knock frequency, the several band-pass filters were designed, converted to biquad filter for ProSAK system, and then compared. Knock intensity from experiments are displayed in Figure 5 and Figure 6. These results are based on choosing appropriate combustion windows and reference windows.

Table 3 Knock Control Parameters

Item	Pilot SOI	Diesel Split Ratio	Gas Ratio
Reduce knock control	$\Delta a_{b1} = 3$	$\Delta a_{b2} = -0.05$	$\Delta a_{b3} = 0.05$
Drain knock control	$\Delta a_{s1} = 0.05$	$\Delta a_{s2} = -0.001$	$\Delta a_{s3} = 0.001$
Max Adjustment	$a_{k1,\max} = 12$	$a_{k2,\max} = -0.4$	$a_{k3,\max} = 0.2$
Output Saturation	-	$a_{e2(\min-\max)}$ (0.3-1)	$a_{e3(\min-\max)}$ (0-0.8)
Conditional Criterion	-	diesel split ratio > 0.70	gas ratio < 0.65

Figure 5 (left) showed the knock intensity of cylinder#1 to cylinder#4 with 0.9-1.1 kHz band-pass filter. Background knock intensity is approximate to 500. While simulating knock during 12-17 seconds, no steep increase of knock intensity is displayed or no knocking energy was found. Figure 5 (right) shows the results with 7-9 kHz band-pass filter which demonstrate at around 800 of knock intensity in cylinder #2 during engine knock.

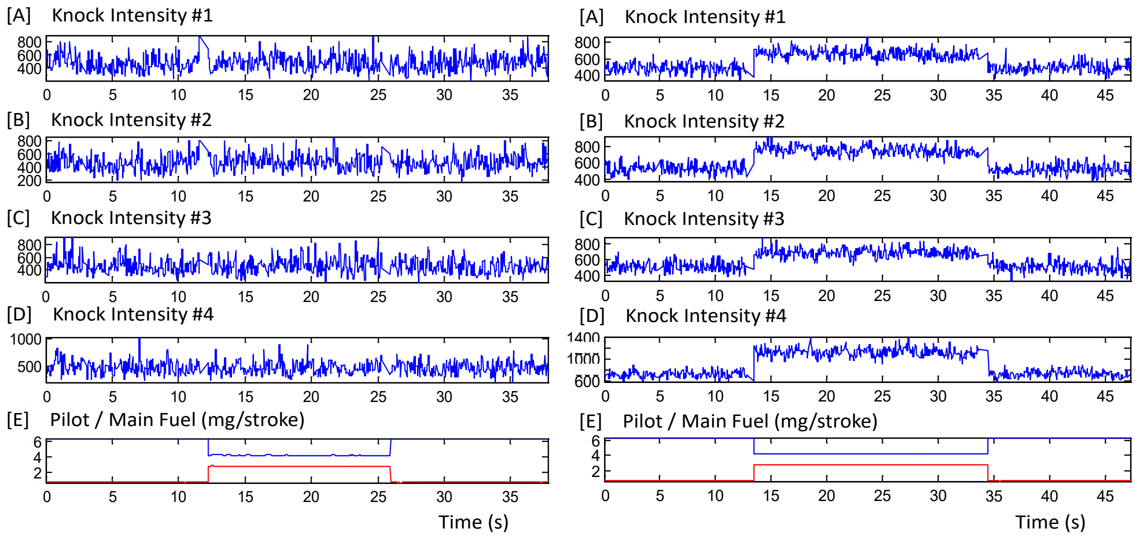

Figure 5 (left) Knock intensity with 0.9-1.1 kHz band-pass filter,
(right) Knock intensity with 1-3 kHz band-pass filter

With implementing the 4-6 kHz band-pass filter, the knock intensity is significantly generated corresponding to engine knock as shown in Figure 6 (left). During knock simulating between 25-26 second, knock intensity rises from 2,000 to 6,000. The frequency range is a good selection for a band-pass filter to capture the knocking frequency content. Figure 6 (right) displays poor results of 7-9 kHz band-pass filter which less knocking energy is in the range.

Other most relevant parameters in knock detection system are knock window and reference window. The tests were performed on fixed engine speed and load as same as the previous one. No band-pass filters were included for following results.

Because this DDF engine applies early diesel pilot injection, the knock occurrence is difference from conventional SI or CI engines. Figure 7 (left) shows the knock intensity of cylinder#1-cylinder#4 when window selection is suitable for conventional DDF engine knock; which is prone to occur after TDC. From the experiments, the results from appropriate windows for our DDF engine are shown in Figure 7 (right). The knock intensity captures engine knock of all cylinders.

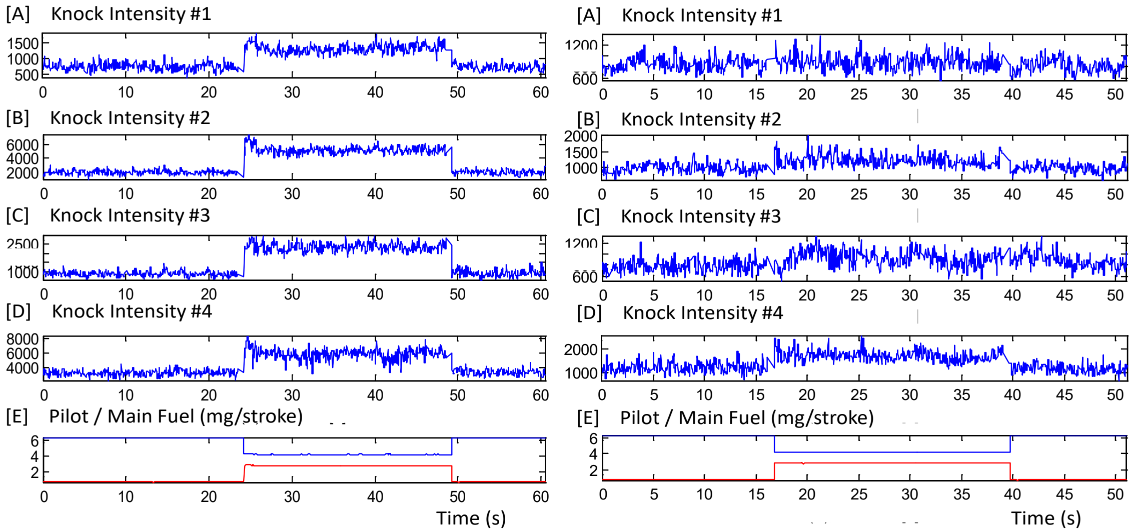

Figure 6 (left) Knock intensity with 4-6 kHz band-pass filter,
(right) Knock intensity with 7-9 kHz band-pass filter

The appropriated knock detection is placed in the sensor model of the knock control system. During steady-state engine calibration, there is no engine knock over entire engine operational range. But there are uncontrolled parameters that lead to engine knock such as intake temperature, fuel quality (diesel and CNG) as well as other engine parameters that varying during transient operation.

To evaluate the control performance, experiments were performed on Toyota Hilux Vigo vehicle's road tests. Figure 8 (left) is the case of no control. In this transient operation, knock occurred after the engine was running on high gas ratio which it accumulated heat in the cylinders. When engine was switched to pilot injection strategy, knock occurrence was found. Using pilot injection strategy in steady-state condition, engine efficiency is high and emissions are low, but the combustion is very sensitive to parameter variation. The top figure shows knock intensity (solid line) and the moving average (dashed line) while knock occurred during 13-16 seconds. Pre-calibrated fuel-path variables during the tests are displayed as follows: diesel main injection quantity (solid line), diesel pilot injection quantity (dashed line) and CNG quantity (dotted line) are shown Figure 9B (left). Diesel main SOI (solid line) and diesel pilot SOI (dash line) are shown in Figure 9C (left).

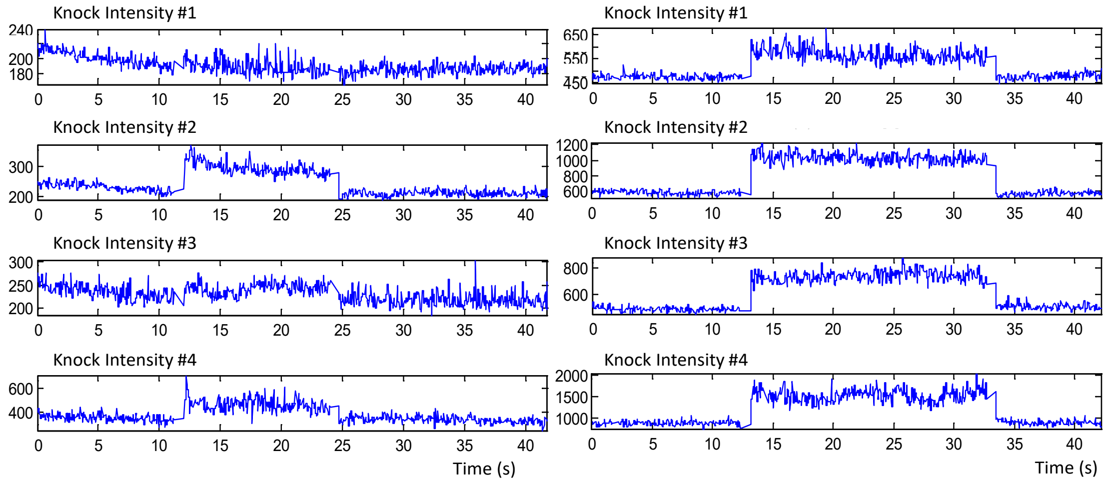

Figure 7 (left) Knock intensity with reference window (50, 0), knock window (-20, -50), (right) Knock intensity with reference window (50, 20), knock window (10, -50)

Figure 8 (right) is the case of knock control with pilot SOI adjustment. Without the controller, knock should occur during the pilot strategy between 15-17 seconds. But the controller reduced engine knock by adjusting the pilot SOI as shown in Fig 8D (right). Figure 9 (left) shows the case of knock control with pilot SOI and diesel spilt ratio adjustment. The knock intensity was controlled at low level from 12-18 seconds. Figure 9 (right) shows the case of knock control with pilot SOI, diesel spilt ratio and gas ratio adjustment. Three variables were adjusted simultaneously which the knock intensity was controlled well below 600. In this case, increasing of CNG quantity partially reduced the engine knock as well as the other variables were less adjusted from original maps. Moreover, natural gas utilization was increased from 55% to 70% which shown in Figure 10F (right). It is indicates that the total fuel price was reduced.

CONCLUSIONS

The knock identification and control algorithm were implemented on a production ECU. The 4-6 kHz band-pass filter was selected to capture knock frequency content. Reference window from 50 to 20 dbTDC and knock window from 10 to -50 dbTDC were selected to knock detection system.

From the road tests, the multivariable controller regulated knock intensity at desired knock threshold during the transient operation by adjusting pilot SOI, diesel spilt ratio and gas ratio. For each knock occurrence, advanced Pilot SOI is the primary control which is adjusted 3 degrees and maximum at 12 degrees. For each execution, 5% of diesel pilot injection reduction and 5% of CNG increasing are secondary control, and they are limit at 40% and 20%, respectively.

From 2012, author implemented hundreds of semi-commercial ECUs for Diesel-dual-fuel (DDF) trucks in Thailand. This proposed algorithm is practical methodology for implementing on DDF trucks because it is based on a commercial IC and requires low computational resource. The knock detection and reduction algorithm ensure the engine longevity. Future work includes performing tests for all operating condition and implementing adaptive control in order to ensure performance with varying fuel quality and engine wear.

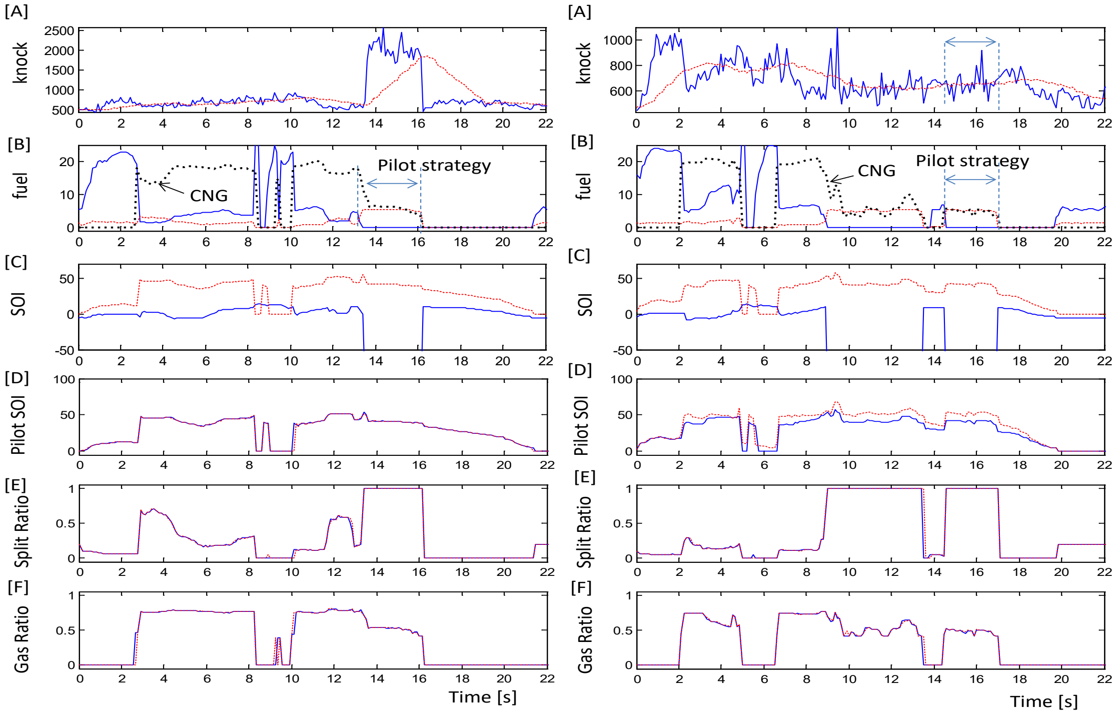

Figure 8 (left) Knock on road load tests without control,

(right) Knock control using pilot SOI adjustment

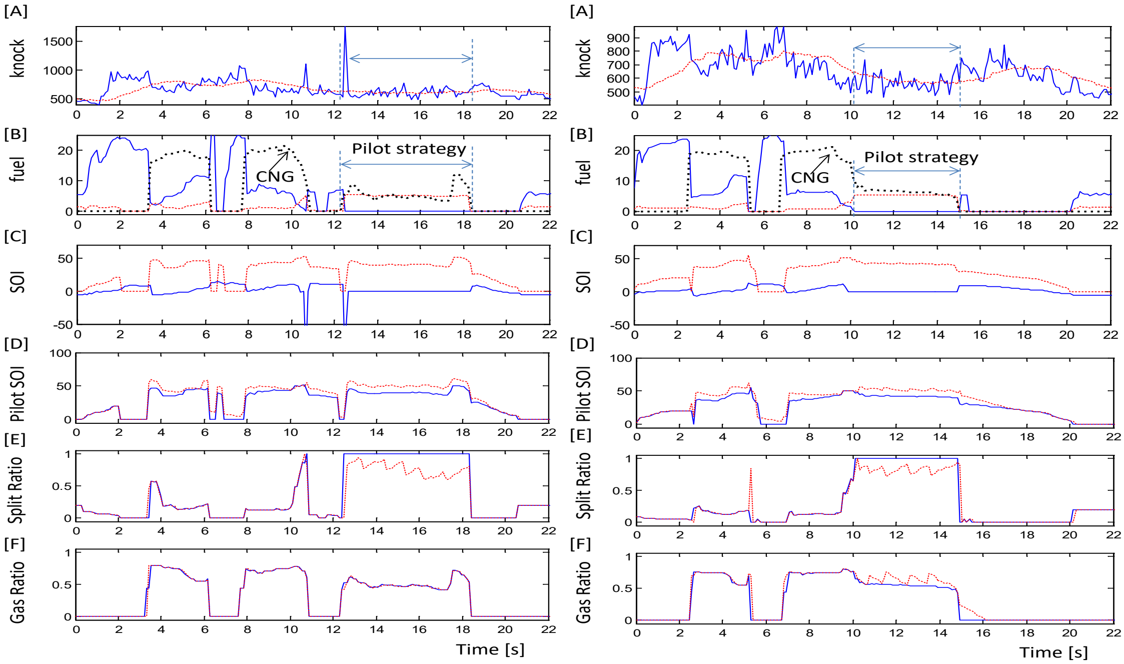

Figure 9 (left) Knock control using pilot SOI /diesel spilt ratio adjustment,

(right) Knock control using pilot SOI /diesel spilt ratio/gas ratio adjustment

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