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Engine Torque Control of Spark Ignition Engine using Fuzzy Gain Scheduling

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Abstrak

Pada sistem mesin bakar dengan penyalaan busi (spark ignition engine), kenyamanan pengemudi dalam berkendaraan sangat tergantung pada pemenuhan torsi mesin sesuai dengan posisi pedal gas yang dimasukkan pengemudi. Namun sayangnya, seringkali pemenuhan torsi mesin tidak sejalan dengan upaya penghematan bahan bakar. Permasalahan ini membutuhkan pengembangan pengendali yang kinerjanya bagus dan kokoh dalam setiap operasi mesin. Salah satu upaya untuk keperluan ini adalah dengan melakukan pengaturan torsi mesin menggunakan penjadwalan penguat fuzi. Dengan menggunakan metode ini, pembukaan pedal gas yang diberikan oleh pengemudi akan dikoreksi sehingga mengikuti masukan referensi torsi mesinnya dan sekaligus melakukan upaya pengurangan konsumsi bahan bakar. Pada kasus ini, dilakukan proses pengaturan torsi mesin pada sistem mesin bakar dengan penyalaan busi dengan transmisi otomatis (automatic transmission).

Kata kunci: *spark ignition engine, torsi mesin, fuzzy gain scheduling.*

Abstract

In the spark ignition engine system, driver convenience is very dependent on satisfying engine torque appropriate with the throttle position given by the driver. Unfortunately, sometimes the fulfillment of engine torque is not in line with fuel saving efforts. This requires the development of high performance and robust power train controllers. One way to potentially meet these performance requirements is to introduce a method of controlling engine torque using fuzzy gain scheduling. By using this method, the throttle opening commanded by the driver will be corrected by throttle correction signal that guarantees engine torque output will follow the desired engine torque input, and also reducing fuel consumption. In this case, spark ignition engine with automatic transmission is used to meet a good performance under this controller design.

Keywords: *spark ignition engine, engine torque, fuzzy gain scheduling.*

1. Introduction

Over the last three decades there has been a dramatic evolution in spark ignition engine control systems, largely driven by government regulations and policies aimed at improving fuel economy and reducing emissions. It is increasingly important to achieve control over transient behavior and meet performance objectives over the life of the vehicle. This requires the development of high performance and robust power train controllers. The performance objectives are often conflicting, or at best interrelated. Due to this reasons controlling of automotive engines is needed.

Control of automotive engines [1] focuses on a variety of problems, including control of idle speed, spark timing, air-fuel ratio, and engine torque. Various studies have been done to these efforts, some of which focus on controlling the engine speed and manifold pressure [2]–[5]. The problem is controlling the engine speed and manifold pressure has not been able to provide solutions to the needs of large torque which at times appear more responsive. Another approach that proved more effective is by controlling engine torque [6]-[8]. By controlling engine torque automatically increases vehicle performance: driving convenience, improving fuel economy and reducing emissions. This happens because the maximum engine torque can be achieved only by doing perfect combustion of fuel in the combustion cylinders, meaning to maintain perfect combustion of fuel usage to be effective and efficient.

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There are several methods in application of engine torque control, i.e. by regulating ignition time, air-to-fuel ratio, and throttle position. In [9] and [10] was performed engine torque control by regulating ignition time, this strategy done well in fuel saving but not give maximum results in engine torque tracking. Similarly, in [11] was performed engine torque control by regulating air-to-fuel ratio, the results obtained is also not optimal in engine torque tracking.

This paper focuses in particular on engine torque control by regulating throttle position and maintains air-to-fuel ratio and time ignition as close as possible to ideally yield perfect combustion. The goal is to develop algorithms which can control engine torque well, thus providing adequate fuel control and driving convenience to driver. One way to potentially meet these performance requirements is to introduce a method of controlling engine torque using fuzzy gain scheduling, since many fuzzy application have been developed in engine and vehicle performance development [5], [9]–[12]. By using this method, the throttle opening commanded by the driver will be corrected by throttle correction signal that guarantees engine torque output will follow the desired engine torque input. In this case, spark ignition engine with automatic transmission is used to meet a good performance under this controller design.

2. Spark Ignition Engine with Automatic Transmission

In this research, we use spark ignition engine model as described in [13]. The model is Ford SI-engine model.

The rate of air into the intake manifold can be expressed as the product of two functions; i.e. an empirical function of the throttle plate angle and a function of the atmospheric and manifold pressures, as shown in Equation 1.

$$\dot{m}_{ai} = f_1(\theta) f_2(P_m) \tag{1}$$

where

$\dot{m}_{ai}$ = mass flow rate into manifold (g/s), with

$f_1(\theta) = 2.821 - 0.05231\theta + 0.10299\theta^2 - 0.00063\theta^3$

θ = throttle angle (deg)

$$f_2(Pm) = \begin{cases} 1, & P_m \le \dfrac{P_{amb}}{2} \\ \dfrac{2}{P_{amb}}\sqrt{P_m P_{amb} - P_m^2}, & \dfrac{P_{amb}}{2} \le P_m \le P_{amb} \\ -\dfrac{2}{P_m}\sqrt{P_m P_{amb} - P_m^2}, & P_{amb} \le P_m \le 2P_{amb} \\ -1, & 2P_m \ge 2P_{amb} \end{cases}$$

P_m = manifold pressure (bar)

P_{amb} = ambient (atmospheric) pressure (bar), 1 bar

The intake manifold can be modeled as a differential equation for the manifold pressure, as shown in Equation 2.

$$\begin{aligned} \dot{P}_m &= \frac{RT}{V_m}\left(\dot{m}_{ai} - \dot{m}_{ao}\right) \\ &= 0.41328\left(\dot{m}_{ai} - \dot{m}_{ao}\right) \end{aligned} \tag{2}$$

where

R = specific gas constant

T = temperature (^{o}K)

V_m = manifold volume (m^3)

$\dot{m}_{ao}$ = mass flow rate of air out of the manifold (g/s)

$\dot{P}_m$ = rate of change of manifold pressure (bar/s), with $P_0 = 0.543$ bar

The mass flow rate of air that the model pumps into the cylinders from the manifold is described in Equation 3 by an empirically derived equation.

$$\dot{m}_{ao} = -0.366 + 0.08979NP_m - 0.0337NP_m^2 + 0.0001N^2P_m \quad (3)$$

where
$\dot{m}_{ao}$ = mass flow rate of air out of the manifold (g/s)
N = engine speed (rad/s)
P_m = manifold pressure (bar)

The torque developed by the engine is described as in Equation 4.

$$T_e = -181.3 + 379.36m_a + 21.91(A/F) - 0.85(A/F)^2 + 0.26\sigma - 0.0028\sigma^2 + 0.027N - 0.000107N^2 + 0.00048N\sigma + 2.55\sigma m_a - 0.05\sigma^2 m_a \quad (4)$$

where
m_a = mass of air in cylinder for combustion (g)
A/F = air to fuel ratio
σ = spark advance (degrees before top-dead-center/TDC)
T_e = torque produced by the engine (Nm)

Fuel consumption can be estimated with air-to-fuel ratio estimation (*A/F*) and mass of air in cylinder for combustion ($m_a \approx m_{ao}$) in Equation 3; as shown in Equation 5.

$$Fuel = \frac{m_a}{A/F} \quad (5)$$

where
$Fuel$ = fuel consumption (g)
m_a = mass of air in cylinder for combustion (g)
A/F = air to fuel ratio

The engine torque less the impeller torque results in engine acceleration; as in Equation 6.

$$I_{ei}\dot{N} = T_e - T_L \quad (6)$$

where
I_{ei} = engine rotational + impeller moment of inertia (kg-m^2) = 0.14 kg-m^2
$\dot{N}$ = engine acceleration (rad/s^2), with initial engine speed N_0 = 209.48 rad/s
T_e = torque produced by the engine (Nm)
T_L = load torque (Nm)

Load torque (T_L) generally produced by vehicle dynamics. The vehicle model with 4-step automatic gear transmission that used in this engine model application is derived based on state-flow model as in [13].

3. Engine Torque Management Strategy

Basically, the engine torque management strategy use throttle opening control function, air to fuel ratio (AFR), and ignition timing simultaneously to produce desired engine torque [8]. In practical reality, desired engine torque does not exist, because the input given by the driver on the system is the position of the accelerator pedal (pedal position). For that reason, the engine torque control strategy known as the mapping between the position of throttle opening (pedal position) and engine speed with engine torque command [6]. Figure 1 shows the mapping for economical vehicle feel. Desired engine torque as output reference in engine torque control system is determined using this mapping.

In this research, engine torque control regulation conducted only by controlling throttle plate angle. As assumed in introduction that maximum engine torque can be achieved only by doing perfect combustion of fuel in the combustion cylinders, we used AFR and ignition time left on the standard setting that ideally yield perfect combustion, i.e. at 14.7 AFR and the spark advance to 15 degree BTDC respectively [14].

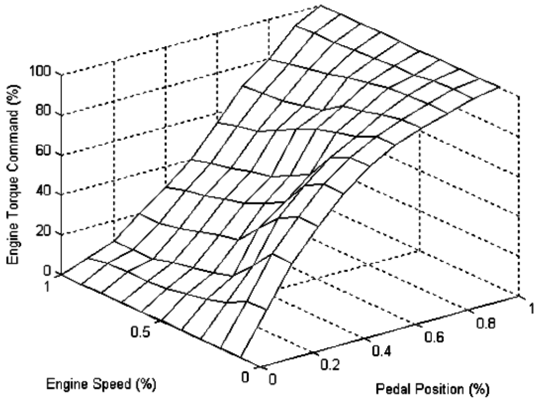

Figure 1. Mapping pedal position and engine speed with engine torque command for economical vehicle feel [6]

4. Fuzzy Logic Controller as Gain Scheduling

Fuzzy logic controller is one of the controllers based on if-then rules that can be used for decision making as the human mind [15]. It can be embedded on a microcontroller system, and effectively applied as intelligent controllers separately from complex computer systems [16]. At this research, Takagi-Sugeno fuzzy inference mechanism [17] with the input engine torque error and derivative error and output weighting to absolute gain control is used to determine the correction to the throttle plate angle given by the driver.

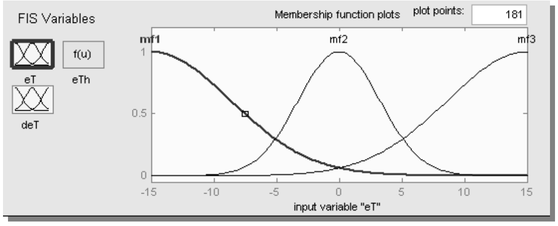

Figure 2. Membership functions of engine torque input error

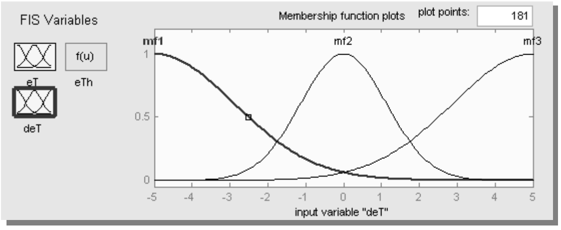

Figure 3. Membership functions of input derivative engine torque error

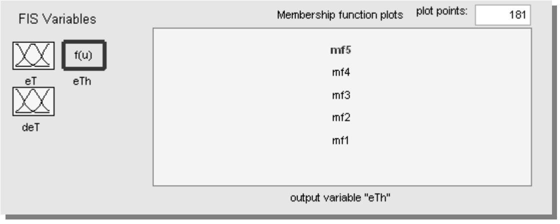

Figure 4. Membership functions of the gain schedule (*mf1 = 0, mf2 = 0.25, mf3 = 0.5, mf4 = 0.75, mf5 = 1*)

Figures 2, 3, and 4 shows membership functions of input and output fuzzy logic controller to be used. As *eT* is *error* between *desired engine torque* and *actual engine torque*, *deT* is *derivative of eT*, and *eTh* is *gain schedule of the throttle position change* that must be added to the throttle input (by driver). We used universe of discourse of those appropriate input and output as: *eT* = [*-15, 15*], *deT* = [*-5, 5*], and *eTh* = [*0, 1*] as *eTh* is used as *gain schedule*.

Rules of inference mechanism used are as follows:

1. *If (eT is mf1) and (deT is mf1) then (eTh is mf1)*
2. *If (eT is mf1) and (deT is mf2) then (eTh is mf2)*
3. *If (eT is mf1) and (deT is mf3) then (eTh is mf3)*
4. *If (eT is mf2) and (deT is mf1) then (eTh is mf3)*
5. *If (eT is mf2) and (deT is mf2) then (eTh is mf4)*
6. *If (eT is mf2) and (deT is mf3) then (eTh is mf5)*
7. *If (eT is mf3) and (deT is mf1) then (eTh is mf4)*
8. *If (eT is mf3) and (deT is mf2) then (eTh is mf5)*
9. *If (eT is mf3) and (deT is mf3) then (eTh is mf5)*

5. Simulation and Analysis

Simulations performed with Matlab Simulink as shown in Figures 5 and 6. The simulation results of engine torque output from three types of control modes (i.e. standard spark ignition engine without controller, spark ignition engine with PID controller, and spark ignition engine with fuzzy gain scheduling controller) with various throttle input are compared as shown in Figures 7, 8, and 9.

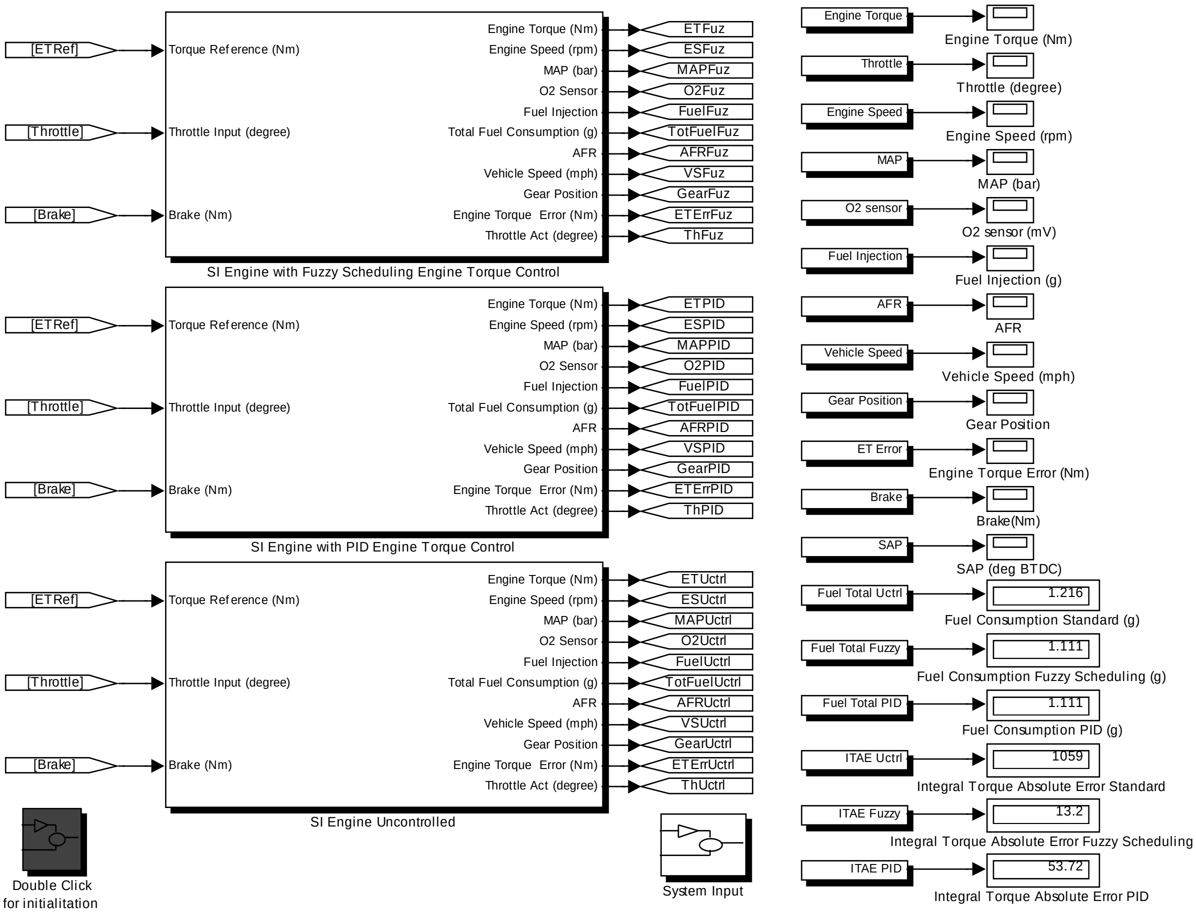

Figure 5. Simulation main model using Matlab Simulink Toolbox

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Other results as integral engine torque absolute error (*ITAE*, i.e. integral of absolute error between actual engine torque output with desired engine torque input which calculated from engine torque mapping for economical vehicle feel as in Figure 5 and total fuel consumption (i.e. integral of fuel consumption as in Equation 5) from appropriate control mode simulations are shown in Table 1.

From Figures 7 and 8 can be seen that at constant throttle input, the transmission gear position changes also affect engine torque output (detected by a dramatically changes on engine torque output during standard engine simulation). As shown, fuzzy gain scheduling controller proved able to effectively reducing this disturbance, while the use of the PID controller still looks a little deviation. Engine torque output overshoot also occurs at step-up/step-down throttle input, where the overshoot by performing fuzzy gain scheduling controller is smaller than performing PID controller. Both of these facts indicate that the fuzzy gain scheduling controller can work effectively for tracking of desired engine torque smoother (this will improve the convenience for the driver).

Similarly, as shown in Figure 9 (the throttle input is sinusoidal), the fuzzy gain scheduling controller works well and smoother than the PID controllers which still indicate a slight disturbance when changing the transmission gear position and slightly lagging to the reference. It also affects the convenience of the driver, as performing fuzzy gain scheduling controller better than performing PID controller.

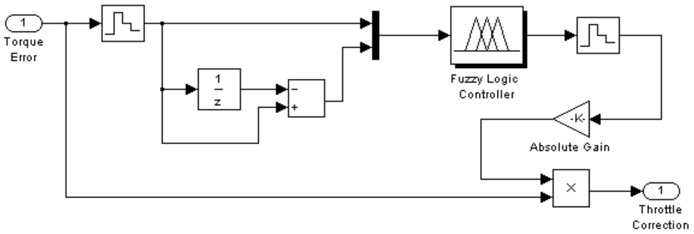

Figure 6. Fuzzy gain scheduling simulation sub-model using Matlab Simulink Toolbox

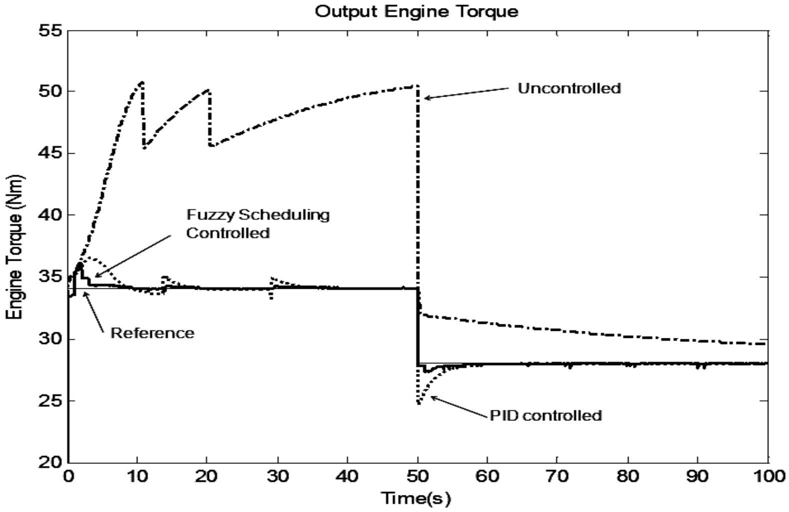

Figure 7. Simulation result for engine torque output with step-down throttle input

From Table 1, it can be seen that performing fuzzy gain scheduling controller effectively reduce error between desired engine torque input and actual engine torque output (*ITAE – Integral Engine Torque Absolute Error*) by improvement average about 10774.678% to the standard application, better than by performing PID controller with improvement average about 2792.751% to the standard application. But there was no improvement significantly to the PID controller for fuel consumption indicator, since fuel saving not too different between both controller for about 12.812% and 12.744% from standard engine, respectively.

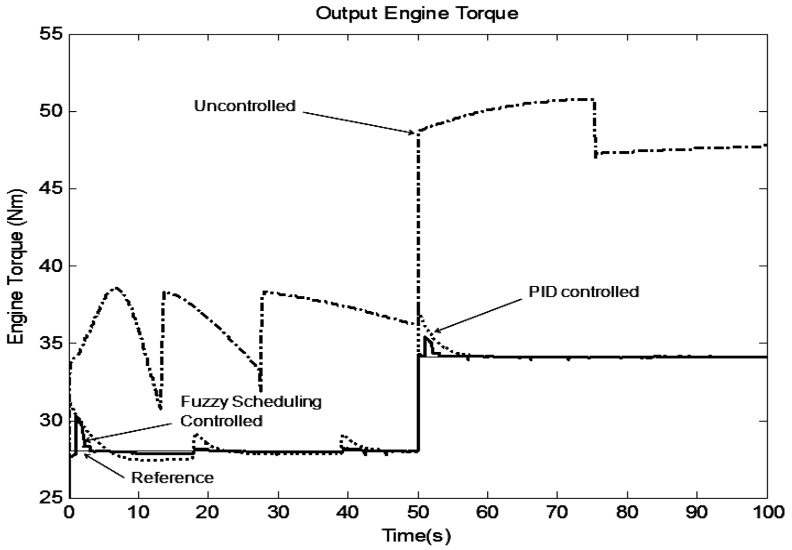

Figure 8. Simulation result for engine torque output with step-up throttle input

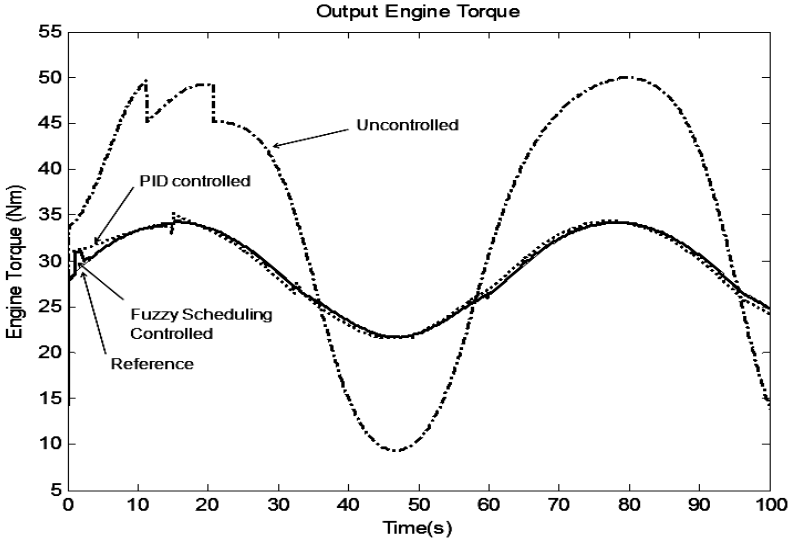

Figure 9. Simulation result for engine torque output with sinusoidal throttle input

Table 1. Simulation result statistical data: ITAE and Fuel Consumption

Simulation Type	Control mode	ITAE		Fuel Consumption	
		Value	Improvement	Value (g)	Improvement
Step-down Throttle Input	Standard	782.300	-	1.276	-
	Fuzzy Gain Scheduling	8.414	9197.600%	1.142	11.734%
	PID	28.910	2606.920%	1.142	11.734%
Step-up Throttle Input	Standard	1164.000	-	1.339	-
	Fuzzy Gain Scheduling	7.606	15203.708%	1.142	17.250%
	PID	29.100	3900.000%	1.144	17.046%
Sinusoidal Throttle Input	Standard	1059.000	-	1.216	-
	Fuzzy Gain Scheduling	13.200	7922.727%	1.111	9.451%
	PID	53.720	1871.333%	1.111	9.451%
Average:	*Standard*	*1001.767*	-	*1.277*	-
	Fuzzy Gain Scheduling	*9.740*	*10774.678%*	*1.133*	*12.812%*
	PID	*37.243*	*2792.751%*	*1.132*	*12.744%*

Note:

- *ITAE = total integral engine torque absolute error (in 100 seconds engine running).*
- *Fuel Consumption = total fuel consumption (in 100 seconds engine running).*
- *Improvement calculated based on Standard mode to appropriate control mode (in %).*

6. Conclusion

From this research can be concluded that the use of knowledge-based control system applications as fuzzy gain scheduling will be very beneficial to overcome control problems with performance index contradictory as optimizing engine torque and reducing fuel consumption on spark ignition engines. Fuzzy gain scheduling controller can work effectively for tracking of desired engine torque smoother (this will improve the convenience for the driver) then performing PID controller or standard engine application (uncontrolled). It also good effort for saving fuel consumption from engine standard application, but there was no improvement significantly to the PID controller application, since fuel saving not too different between both controllers. For future works, air-to-fuel ratio and ignition time must be involved as control action since fuel consumption saving can be improved by changing both of these parameters.

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