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An Experimental Characterization for Injection Quantity of a High-Pressure Fuel Injector in GDI Engines

Wen-Chang Tsai
Department of Electrical Engineering
Kao Yuan University, Luju 82151, Kaohsiung City, Taiwan
Correspondence: t20045@cc.kyu.edu.tw; Tel.: +886-7-6077018

Abstract: In GDI engine applications, high-pressure (H.P.) injectors typically require to be designed to be capable of rapid response for GDI engines in order to be driven in the rapid response with respect to magnetic actuators, allowing for example more precise air-fuel ratio control in the GDI engines. The H.P. fuel injector is a highly dynamic component requiring careful voltage and pressure input modulation to achieve the required fuel injection quantities of GDI engines. The accurate fuel injection curves are a key influence for this technology, therefore will require the estimation of the fuel flow rate to be realized. In this paper, a PIC microchip for programming injector drive circuits is implemented to improve the performance of a H.P. fuel injector and tested to verify its feasibility. In the proposed injector drive circuit, powers MOSFETs directly control the charging/discharging current by a dsPIC30F4011 microchip. Design and analysis of the proposed injector drive circuit are presented. Next, effects of total pulse width, injector supply voltage, fuel system pressure and PWM operation on fuel injection quantities of a H.P. fuel injector are measured. Also, the measured data of the H.P. fuel injector fed by the injector driving circuit are defined as the fuel injection curves. Finally experimental results are provided for verification of the proposed injector drive circuit.

Keywords: dsPIC30F4011 microchip, Injector Driving Circuit, Fuel Injection Curves, GDI Engines

Nomenclature

Symbols	Description	Unit
H.P.	High-pressure	bar
GDI	Gasoline-direct-injection	
AFR	Air-fuel ratio	
MOSFET	Metal oxide semiconductor field effect transistor	
PWM	Pulse width modulation	
ECU	Electronic control unit	
PFI	Port fuel injection	
PCB	Printed circuit board	
TDC	Top dead center	
rpm	revolutions per minute	
Ip1	First turn-on pulse signal	
mfuel	Fuel injection mass	g
tp	Injection pulse duration	μs

1. Introduction

Many advanced solenoid fuel injection techniques have been developed to implement in various investigations of GDI engines [1-3]. The electronic unit injector is the major component in the high pressure fuel injection system. The injector driving circuit was optimized and projected to generate optimal values of two stage currents by a coupled simulation of injector electromagnetic, needle rigid body motion and computational fluid dynamics model [4]. Two-stage current shapes were found to be the optimal power strategy for driving the fuel injector under different supply pressures. It helps us to get a better analysis of the performance of the driving circuits [5]. The injector drive

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circuit was optimized by controlling the current across the solenoid, which further increased the response speed of the valve. Experimental results show that current drive circuit is feasible and reliable to implement for practical applications [6]. The development of an electrical drive for the high-pressure GDI injector was studied for a 500cc motorbike engine. A programmable injector drive circuit is designed and simulated by using PSpice software. Three-stage driving current (two pulse time and adjustable PWM duties) can be optimized by a predetermined current control algorithm [7]. The different types of power losses associated with a solenoid injector were investigated with the help of software simulation. There were remarkable differences in the power losses and the performances of the injector, when it worked within different driven strategies. Simulation results of power losses were validated by comparing to experimental results [8]. Various electrical driving circuit designs for the H.P. fuel injector are proposed and the experimental data of the H.P. fuel injection system are investigated [9-10].

In this study, injector driving circuits are designed to satisfy the rapid response and sustain the instantaneous surge currents for various H.P. GDI injectors. The designed electric driving circuit is tested to verify its feasibility. The experiment for the GDI injection quantities is conducted under 60-100 bar fuel pressure, 1200-2000μs injecting pulse duration and DC 40~70V executing supply voltage. Also, PWM on/off control operation is introduced to the holding current during the last pulse duration for rapid response time to turn off the GDI injector. Design and analysis of the proposed injector drive circuit are presented in the paper. Next, effects of total pulse width, injector supply voltage, fuel system pressure and PWM operation on fuel injection quantities of a H.P. fuel injector are measured and the measured data of the H.P. fuel injector fed by the injector driving circuit are defined as the fuel injection curves. Fig. 1(a) illustrates the cylinder head of the PFI engine. The specifications of the base engine with the PFI injection are shown in Table 1. Fig. 1(b) shows a schematic picture of this PFI engine with certain modifications in its cylinder head. Limited by the structure of the cylinder head, the fuel injector and the spark plug are respectively center-mounted at an induced angle of the left-hand 100 and the right-hand 120 to the vertical plane between the intake and exhaust valves. A testing study is carried out on the modified KYMCO Xciting-500 GDI engine. Experimental configuration of a 500c.c. GDI engine system is shown in Fig. 2. Results show that the H.P. fuel supply system for GDI engines is capable of operating stably and assuring the accurate injection quantities by the three-pulse power MOSFETs electric driving circuit.

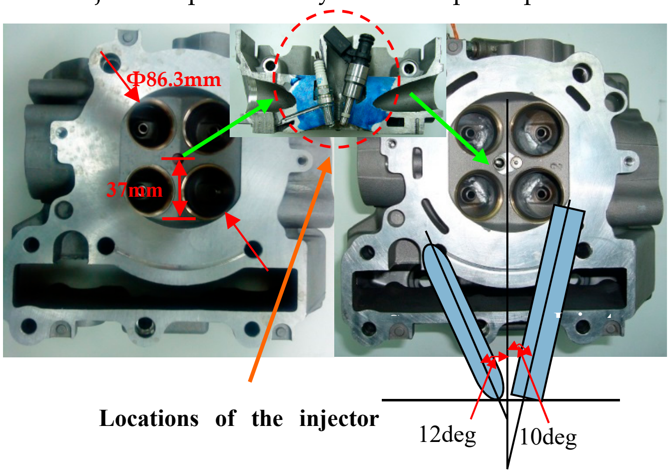

Fig. 1(a) Cylinder head of the PFI engine

Fig. 1(b) Cylinder head of the GDI engine after modification

Table 1 Basic engine specification

Xciting-500cc	
Engine type	single cylinder, four strokes, water cooling
Displacement	498.5mm^3
Bore× Stroke	Φ92×75
Compression ratio	10.5
Maximun power	28.4/7500(kW/rpm)
Maximun torque	4.1/5500(kg-m/rpm)
Ignition method	Crystal
Spark plug	NGK CR7E

2. The High-Pressure GDI Fuel Injection System

In-cylinder direct injection technology is a superior option choice due to its advantages in potential fuel economy and emission reduction. One of the most important technologies is the GDI fuel injecting system, of which the H.P. fuel injector is the central component. A H.P. fuel supply system of GDI engines directly injects fuel to the cylinder of the engine. The injecting timing and duration is electronically controlled by an Electronic Control Unit (ECU). Various pulse durations can be sent to

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the fuel injector according to the engine's actual operating conditions from the signals of engine sensors. The H.P. fuel injection system mainly comprises of four parts: the fuel supply system, electronic control unit (ECU), electrical driving circuit and an injector. The fuel supply system provides a constant 60-100 bar pressure resource for the injector. The injection pulse duration and timing of the injector are controlled by using the Electronic Control Unit (ECU), which computes and analyzes the analogue and digital input signals from various engine sensors. The engine performances can be improved by more rapid engine response in throttle positions, and more precise control of air/fuel ratio. In this study, a Bosch GDI single-hole injector is installed and tested on the cylinder head of a 500c.c. motorcycle engine.

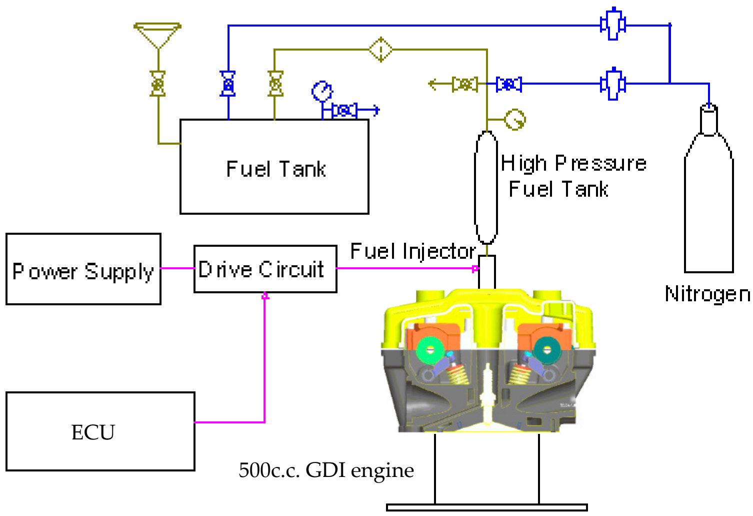

Fig. 2 Experimental test configuration of a 500cc GDI motorbike engine system

2.1. Fuel Supply System

The fuel supply system is similar to the conventional design of GDI engines in H.P. fuel containers. This research adopts a Bosch GDI single-hole injector to be installed in the test device. Its pressure can be operated between 60 and 100 bar (max) which has been commonly used in some GDI engines. In the fuel supply system illustrated in Fig. 2, the H.P. Nitrogen bottle pulls the operating pressure of the stainless fuel cylinder up to 60-100 bar (max). It is expected to maintain this constant value to avoid any disturbances to the GDI injector performance caused by the gasoline pump pressure dip at high speed operation of motorcycle engines. The cylinder pressure is maintained at a constant value through regulating H.P. Nitrogen flow. The pressure fluctuation of the fuel container, caused by closing and opening of the nozzle is about 0.5 bar.

The experimental equipment for characterizing the dynamic performances of the H.P. GDI injector are illustrated in Fig. 3(a). According to the test requirements, the parameters of the fuel injection system are calibrated properly to each part of the injector driving circuit. After the characterization of the injector's dynamic performances, the fuel pressure in the GDI Bosch injector mounted onto a 500c.c. motorcycle engine cylinder head is set at 60-100 bar for the running test.

2.2. High-pressure Fuel Injector

In order to investigate the effect of the total pulse width on the fuel injection quantities, the power voltage is supplied by DC 60 V and the pressure of the fuel supply system were set to and 100 bar. A H.P. GDI injector is preferred for engines with small displacement in relation to the optimum angle of fuel atomization and spray penetration. However, due to the constraints of limited researches into the development of small motorcycle GDI engines, it requires time to design, test, modify and calibrate such a swirl injector. Taking all these into account, the Bosch GDI single-hole injector is adopted based on analyzing the working principle of the electronic controlled injector. The injector is driven by a three-stage current waveform according to the injector characteristics. It

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uses the solenoid valve as electricity-fluid conversion element and controls the injection parameters precisely through the reference current waveforms. The minimum injection quantities is about 1200μs pulse duration and 14.07 mg in each pulse. This satisfies requirements of the idle operation of motorcycle engines. In order to accurately control the expected air-fuel ratio of GDI motorcycle engines, effect of various fuel pressures and pulse widths on fuel injection quantities for the GDI injector fed by the single-pulse (12A) driving current was examined and characterized as illustrated in Fig. 3(b) [7].

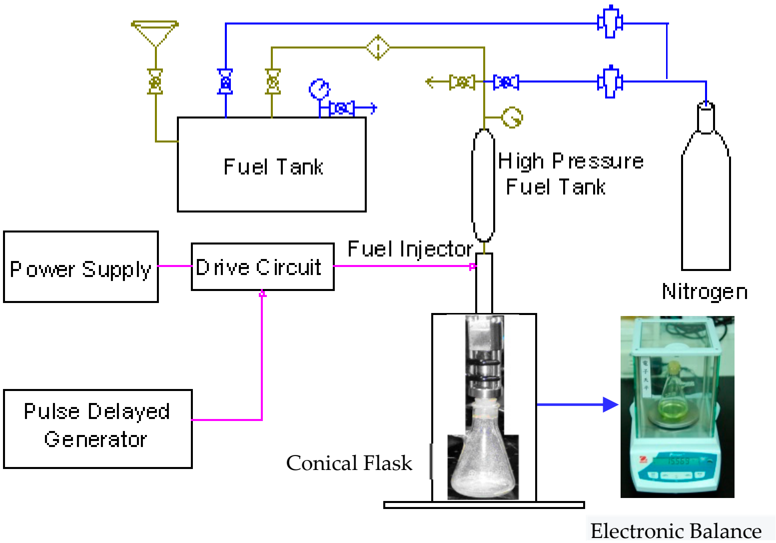

Fig. 3 (a) Injection quantity measurements of the H.P. GDI injector

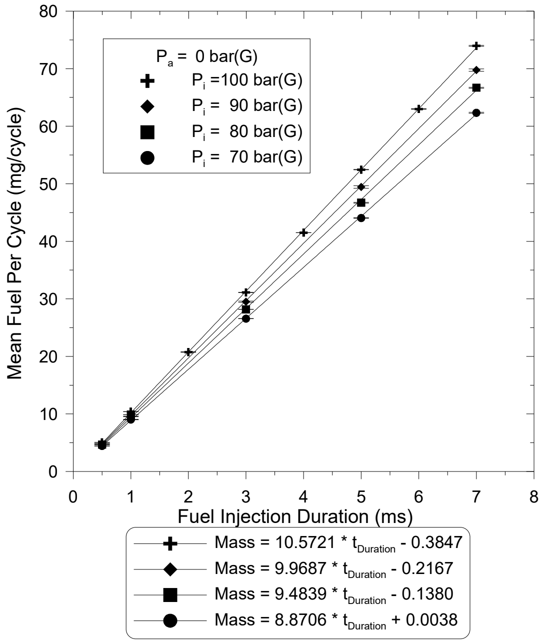

Fig. 3(b) Effect of various fuel pressures and pulse widths on fuel injection quantities of the GDI injector fed by the single-pulse (12A) driving current

2.3 *Mathematical Model:* The H.P. fuel injector system consists of three mainly coupled components: (1) solenoid coil and driver; (2) fuel flow component; and (3) needle lift of injectors. These state submodels can be given by the following nonlinear state model equations. The solenoid coil and driver model will be expressed by the states $\vec{x}_1 = [B\ \dot{B}]^T$, the fuel flow model by the states $\vec{x}_2$ = [P_{bv}], and the needle lift of injectors by $\vec{x}_3 = [x\ \dot{x}\ P_{uv}\ P_{lv}\ u\ \dot{u}\ z\ \dot{z}\ y\ \dot{y}]^T$. α_1 , α_2 , α_3 , β_1 , β_2 , and β_3 are known functions of states and inputs to determine state derivatives or model outputs. [3]

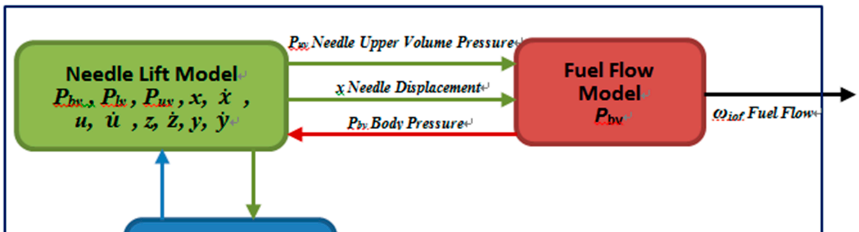

Fig.4 Diagram for mathematic state model of a H.P. fuel injector system.

Solenoid coil driver model:

$$\dot{\vec{x}}_2 = \vec{\alpha}_1(\vec{x}_1,\ \vec{u}_1) = \vec{\alpha_1}\left(\begin{bmatrix}B\\ \dot{B}\end{bmatrix}, \begin{bmatrix}V_{in}\\ u\end{bmatrix}\right) \quad (1)$$

$$\vec{y}_1 = \begin{bmatrix}V_s\\ B\end{bmatrix} = \vec{\beta}_1(\vec{x}_1,\ \vec{u}_1) = \vec{\beta}_1\left(\begin{bmatrix}B\\ \dot{B}\end{bmatrix}, \begin{bmatrix}V_{in}\\ u\end{bmatrix}\right) \quad (2)$$

Fuel flow model:

$$\dot{\vec{x}}_2 = \vec{\alpha}_2(\vec{x}_2,\ \vec{u}_2) = \vec{\alpha_2}\left([P_{bv}], \begin{bmatrix}P_{cyl}\\ x\\ P_{tank}\\ P_{uv}\end{bmatrix}\right) \quad (3)$$

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$$\vec{y}_2 = \begin{bmatrix} P_{vb} \\ \omega_{iof} \end{bmatrix} = \vec{\beta}_2(\vec{x}_2, \vec{u}_2) = \vec{\beta}_2\left([P_{bv}], \begin{bmatrix} P_{cyl} \\ x \\ P_{tank} \\ P_{uv} \end{bmatrix} \right) \quad (4)$$

Needle lift system model:

$$\dot{\vec{x}}_3 = \vec{\alpha}_3(\vec{x}_3, \vec{u}_3) = \vec{\alpha_3}\left(\begin{bmatrix} x \\ \dot{x} \\ P_{uv} \\ P_{lv} \\ u \\ \dot{u} \\ z \\ \dot{z} \\ y \\ \dot{y} \end{bmatrix}, \begin{bmatrix} P_{bv} \\ B \\ PL_{s1} \\ PL_{s2} \\ PL_{s3} \\ PL_{tot} \end{bmatrix} \right) \quad (5)$$

$$\vec{y}_3 = \begin{bmatrix} x \\ P_{uv} \\ u \end{bmatrix} = \vec{\beta}_3(\vec{x}_3, \vec{u}_3) = \vec{\beta}_3\left(\begin{bmatrix} x \\ \dot{x} \\ P_{uv} \\ P_{lv} \\ u \\ \dot{u} \\ z \\ \dot{z} \\ y \\ \dot{y} \end{bmatrix}, \begin{bmatrix} P_{bv} \\ B \\ PL_{s1} \\ PL_{s2} \\ PL_{s3} \\ PL_{tot} \end{bmatrix} \right) \quad (6)$$

where PL_{s1}, PL_{s2}, PL_{s3} , and PL_{tot} are the preloads for the needle upper volume spring, needle return spring, needle lower volume spring, and all injector springs, respectively. The coupling between these subsystem models is shown in Fig. 4. The complete list of states is P_{bv} , P_{lv} , P_{uv} , x, $\dot{x}$, u, $\dot{u}$, z, $\dot{z}$, y, $\dot{y}$, B, and $\dot{B}$.

2.4 Data Acquisition Card and ECU Controller

The Electronic Control Unit (ECU) is designed to be capable of precise A/F ratio control according to the requirements of various engine operating conditions. The injection pulse width and throttle angle can be tuned by the ECU to ensure proper A/F ratio and stable power output requirements (as depicted in Fig. 5). The ECU includes the NI Compact RIO controller, PCI 6221 signal acquisition card, and the PCB board generating the three-stage injection pulses as well as the PWM control signal. The PCI 6221 signal acquisition card collects signals such as engine speed, TDC, throttle

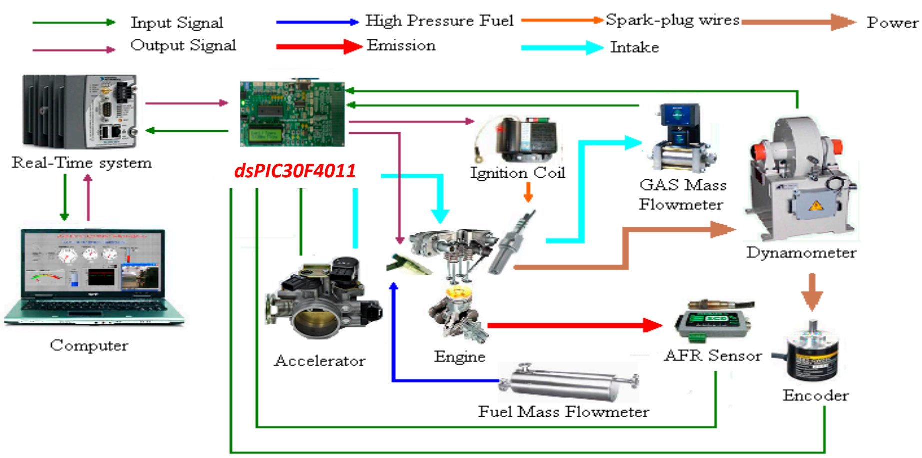

Fig. 5 The Control System Diagram for a 500c.c. motorcycle Engine

position, fuel flow volume, air flow, water temperature and fuel supply pressure etc., received from various engine sensors. These signals are processed and then transmit to the PC for monitoring the operating conditions of motorcycle engines. The NI Compact RIO controller performs a logic

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operation for the A, Z and proximity switch signals of motorcycle engines to determine the TDC on intake and compression of engines. The TDC on compression of engines is a reference (based) point. By the reference point, the ECU performs an arithmetic computation of engine parameters as speed, torque, throttle position, air flow and fuel supply pressure to achieve the delay timing and duration of the injection driving pulse. The PWM control is added to the last pulse duration of injector driving current to rapidly turn off the GDI injector. The pulse and PWM control circuit board outputs the two different duration injection pulses and a last-stage PWM signal to drive the power MOSFETs switches in injector driving circuit. Therefore, the three-stage (12/5/3 A) peak and holding current profiles are generated and supplied to the solenoid valve coils of the injector to induce the electromagnetic force to draw back and hold the nozzle needle of a GDI injector. The configuration of PC_Based control system for the 500c.c. motorcycle engine is illustrated in Fig. 5.

3. Design of Injector Driving Circuit

This research develops various driving circuits for the H.P. fuel supply system of a 500c.c. GDI motorcycle engine. The initial design of the driving circuit for the H.P. GDI fuel supply system is developed by three-stage power transistors. The designed driving circuit was tested in high-frequency driving pulse to execute the experiments of high-speed fuel injection quantities. The antinoise photocoupler 4N35 driving ICs driven by the first and second pulses were usually damaged due to surge voltages and currents exceeding their operating rating. To improve the above faulty design or simplify the driving circuit, three-stage power MOSFETs driving circuits were developed in this study. The GDI injector driving circuits were developed to be a practical printed circuit board (PCB) to test the effect of engine speeds, pressures of the GDI fuel supply system, driver supply voltages, first stage turn-on driving currents, pulse durations and PWM control added to the last pulse duration on the dynamic performance of the GDI injector. Therefore, the power MOSFETs components were adopted to design the GDI injector driving circuit under the operations of high-frequency surge voltages and currents. The procedures for the simulation and practical designs are illustrated as below:

3.1 Injector Driving Circuit

The governing equation is then obtained for the simple resistor-inductor circuit (RL Circuit) using KVL as follows:

$$V_{SC} = I_{SC}\, R_{SC} + L_{SC}\,\frac{dI_{SC}}{dt} \qquad (7)$$

where V_{SC} is the voltage across fuel injector solenoid coils; R_S is the resistance of fuel injector solenoid coils; L_{SC} is the inductance of fuel injector solenoid coils.

From the above equation (7), the coil current is expressed by

$$I_{SC}(t) = \frac{V_{SC}}{R_{SC}}\left(1-e^{-\frac{R_{SC}t}{L_{SC}}}\right) = \frac{V_{SC}}{R_{SC}}\left(1-e^{-\frac{t}{\tau}}\right) \qquad (8)$$

where τ is the electrical subsystem time constant,

The following expression for inductance of the fuel injector solenoid coil is given by[4]

$$L_{SC} = \frac{N^2 \mu_1 \frac{\pi}{4} d^2 h}{\frac{dw}{2} + \Delta_x h} \qquad (9)$$

where,

$\mu 1$= permeability in the air [H/m]

N = number of solenoid coil turns

h = pintle height [mm]

d = pintle disk diameter [mm]

Δ_x= air gap[mm]

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w = non-magnetic strip width [mm]

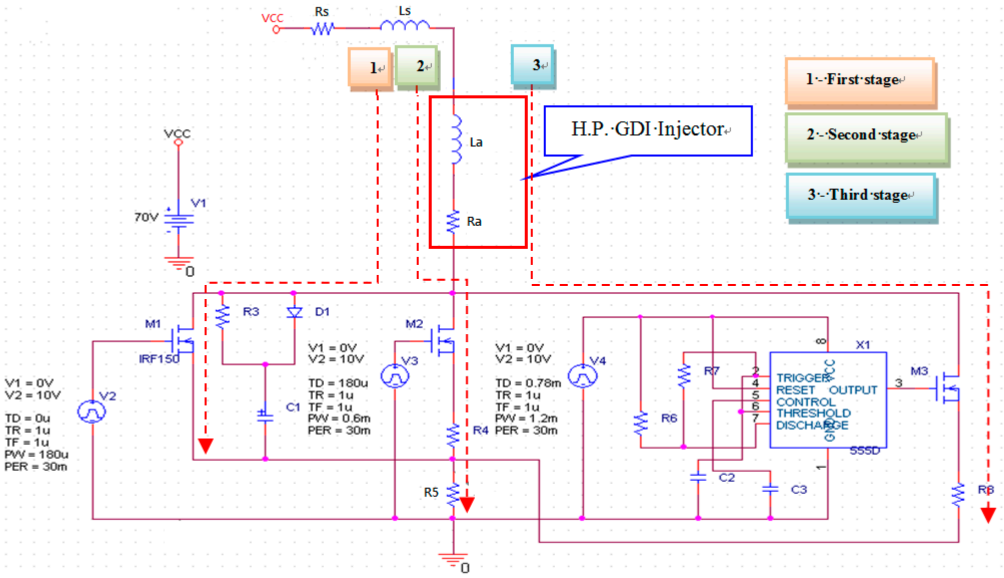

Fig. 6(a) Three-stage power MOSFETS drive circuit for the H.P. GDI Injector with PWM control added to the last pulse duration

In order to carry on the experiments under the operations of high-frequency surge voltages and currents, three-stage power MOSFETs is introduced in the design of the injector driving circuit. The electric driving circuit is designed and simulated for the requirements of the GDI injector characteristics in the Pspice simulation software. The Pspice model of the three-stage power MOSFETs electric driving circuit is illustrated in the Fig. 6(a). After simulation and experimental test, the improved electric driving circuit and PWM control added into the last pulse duration is required to make a practical PCB. The PCB layouts of three-stage driving pulse and PWM control

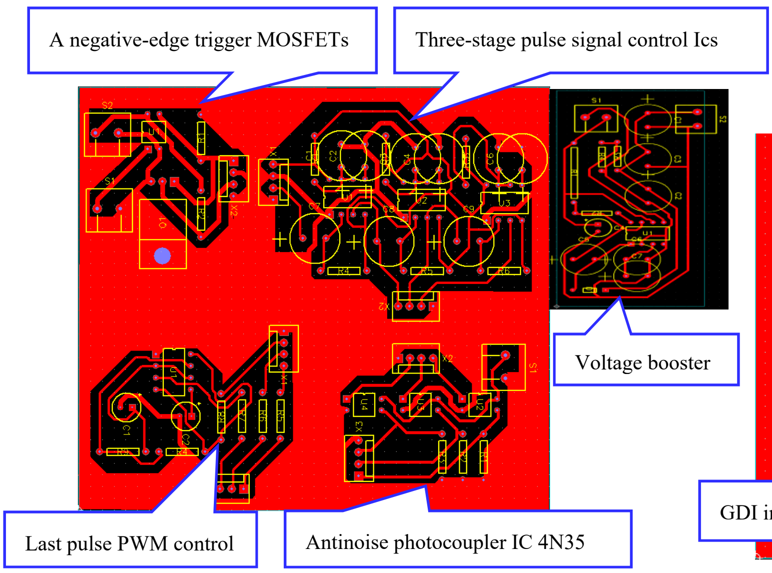

Fig. 6(b) The PCB layout of three-stage driving pulse and PWM control signal added to the last pulse operation

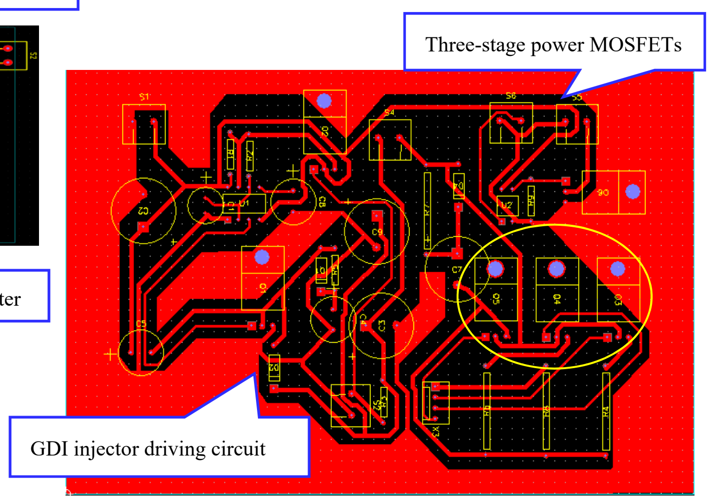

Fig.6(c) The PCB layout of three-stage power MOSFETS drive circuit

signal circuit as well as power MOSFETS drive circuit are presented in Figs. 6(b) and 6(c) respectively. By taking the procedures of exposure, photography development, and metallurgy etching, two circuit boards was developed and then the parts were soldered into the PCB board. In this work, a programmable driving module based on the working principle of the injector electric driving circuit is designed and shown in Figs. 6(d) and 6(e).Three driving pulse signals are supplied to drive the power MOSFETs switches of the electrical driving circuit via the photocoupler driving IC 4N35. The functions of the photocoupler driving IC 4N35 are signal processing and antinoise. The

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DC 5V trigger signals from ECU output are required to raise up to at least 15V voltage level using IC 4N35 photocoupler circuit to be able to drive the power MOSFETs switches M4~M6 as depicted in Fig. 6(a). It may prevent the pulse signals from noise disturbances and protect the logic operation ICs of the signal circuit against the damage of surge voltages and currents due to IGBT switching. Total turn-on injection pulse duration of the GDI injector is set at a range between 1200µs and 2000µs, in which the first, second and third pulse duration are 200µs, 600µs and 400~1200µs respectively. Three pulse signal durations can be determined by resistors at Pin 6 and capacitors connected into the Pin 7 of the ICs. Total pulse duration is limited up to 3000µs. The PWM frequency has been experimentally selected and applied in the last pulse, fm = 30-200(kHz). It considered as the best compromise between reducing current ripple and a limited switching action from the components, therefore ensuring a good injector squirting response.

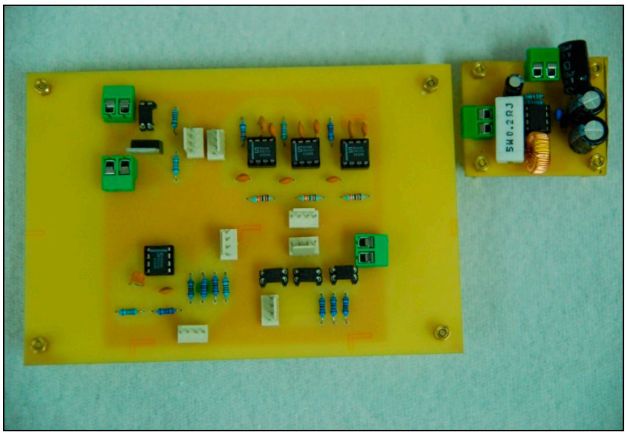

Fig. 6 (d) Practical three-pulse signal circuit board with PWM control added to the last pulse operation

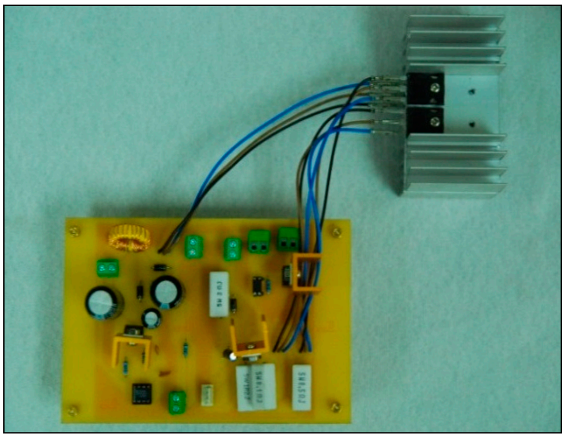

Fig. 6(e) The developed H.P. injector driving circuit board

3.2. Experimental Procedures and Measurement Conditions

Generally, fuel injection quantities of the GDI injector can be controlled by adjusting the driving pulse duration. In order to understand the dynamic performance of a GDI injector, the interrelationships between the parameters of the fuel injecting system and its fuel injection quantities must be investigated. These includes total driving pulse duration, first stage turn-on peak current, the injector driver supply voltage, the operating modes added to third pulse operation to

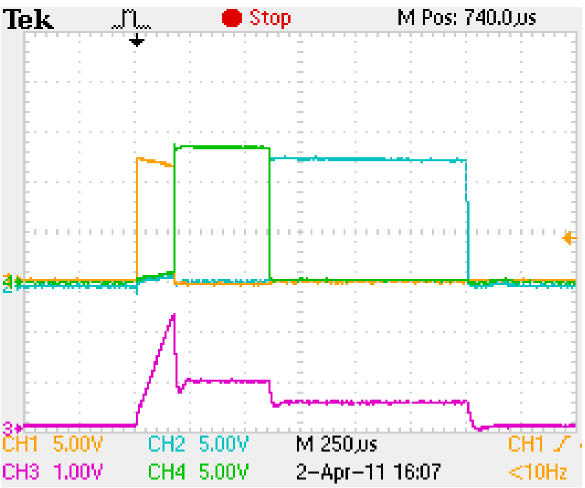

Fig. 7(a) The driving pulse signals and GDI injector current waveforms without PWM control added to the last pulse duration (I_{p1}=200µs)

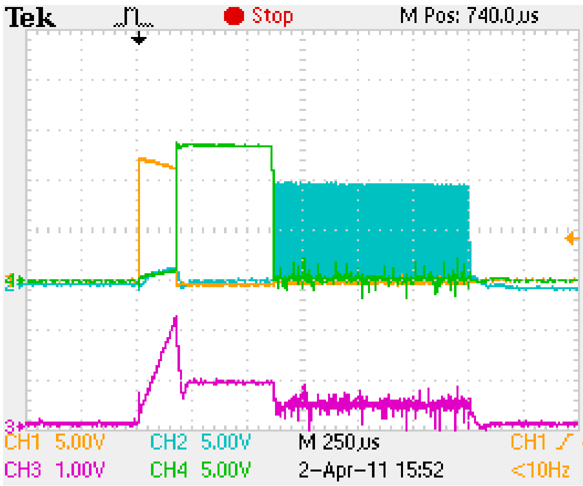

Fig. 7(b) The driving pulse signals and GDI injector current waveforms with PWM control added to the last pulse duration (I_{p1}=200µs)

cut off the injector and the pressure of the fuel supply system. The executing driver supply voltages, output driving pulses and currents for the H.P. GDI injector are measured and displayed on the digital storage oscilloscope so as to meet the operating requirements of the GDI injector. Fig. 7(a) and

7(b) present the experimental driving pulse signals of three different pulse durations and the GDI injector current waveform without and with last pulse PWM control. The yellow waveform represents the first turn-on pulse signal (Ip1=200μs), the 12A current produced is sufficient to rapidly draw back the nozzle needle of the GDI injector when the fuel injecting pressure is set at 100 bar. The second driving pulse as shown in the blue waveform drives the GDI injector to produce the 5A holding current and maintain continuous injection. The last driving pulse is indicated as the pink waveform, the driving circuit supplies the 3A current to hold the nozzle needle of the GDI injector. Meanwhile, the injection status of the GDI injector is carrying on but ready to stop squirting. An injecting pulse signal from ECU is fed into the three-stage power MOSFETs PCB to generate the three-stage (12/5/3A) driving current waveforms. The three-stage currents are supplied to drive the actuators in the GDI injector for carrying out the fuel injection experiments. In the experiments, the driver supply voltage is varied between 40V and 70V. The pressure of the fuel supply system is set at a range between 60 bar and 100 bar. A power MOSFETs-switch GDI driver is designed with a wide range of injection pulse durations (1200~2000μs). The fuel injection quantities for four corresponding engine speed settings, 1200rpm, 2400rpm, 6000rpm, and 9000rpm are measured. After completing 1000 times of fuel injections, the fuel injection quantities is measured in the electronic balance and total measured fuel mass (g) is divided by 1000 to obtain the average fuel injection quantities (mg) per injection. The results characterize the dynamic performances of the GDI injector fed by the electrical driving circuit and provide the engine AFR control with the precise fuel injection quantities to achieve superior dynamic performances of a GDI injector.

4. Results And Discussions

The electrical driving circuit is installed and tested in the GDI injecting system as illustrated in Fig 3(a). Experimental configuration is described in Table 2. Experimental validation was taken based on a single-hole Bosch GDI injector. This type of GDI injector requires the three-stage driving circuits charged by a DC supply voltage to acquire three-stage driving currents. In order to evaluate the operating stability of the GDI injector application, the injection pulse duration is normally defined between 1200~2000μs. The components of the electrical driving circuit are designed to be capable of withstanding the peak voltages and currents. A 5V Square-pulse signal inputted to the electrical driving circuit. The supply voltage is adjusted ranging from DC 40V to 70V and supplied the GDI injector actuator to test the effects of the injector supply voltage on the fuel injection quantities. Finally, experiments for two different first pulse turn-on currents (12/10A) have been conducted and compared in the paper. The experimental configuration for the spray test of the GDI injector and injection performance is observed at first pulse turn-on time (Ip1=200μs) and driving signal duration=1500μs.

Table 2 Experimental configuration

Condition	Description
Supply voltages	DC 40~70V
Current profiles Max	12A/5A/3A
Fuel pressure	60~100 Bars
Fuel temperature	30 °C
Number of injection samples	1000

4.1 Effect of Total Pulse Width

The power supply voltage and the pressure of the fuel supply system are set at DC 60V and 100 bar to measure the fuel injection quantities by adjusting total pulse width. The injecting frequency and driving pulse duration are adjusted at the above sampling speeds to measure the average fuel injection quantities. Effects of various speeds and pulse widths on fuel injection quantities of the H.P. fuel injector fed by the three-stage (12/5/2.5A) driving current are represented in the Fig. 8. The following equations for characterizing the fuel injection curves are given by:

$m_{fuel} = 1.0984\, t_p + 11.567$ between 1200 and 6000 rpm (R_2 =0.9993)

$m_{fuel} = -0.0639 t_p^2 + 1.4758\, t_p + 11.715$ for exceeding 6000 rpm (R_2=0.9968) (10)

where m_{fuel}= Fuel injection mass (g); t_p= pulse duration (μs)

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In the experiment, PWM control is withdrawn from the last pulse duration. As the first driving pulse turns on the MOSFET, the actuator coils of the H.P. fuel injector is charged by the DC 60V supply voltage. The first-pulse turn-on peak currents is, therefore, generated and flow into the solenoid valve coils of the injector to induce the electromagnetic force to draw back the nozzle needle of a H.P. fuel injector. The 100 bar fuel pressure thus forces the fuel into the experimental jar via the nozzle hole. Next, the second and third pulses trigger the second- and third- stages MOSFETs to produce the 5A and 2.5 A holding currents respectively. These two exciting currents charge the solenoid valve coils to hold the nozzle needle of the H.P. fuel injector, therefore the fuel of the H.P. fuel injector would keep spurting. The H.P. fuel injector is operated at an injecting frequency ranging from 10 pulses /s to 75 pulses /s. The injecting frequency is equal to the engine speeds from 1200 to 9000rpm. By adjusting the fuel injection width within a range between 1200μs and 3000μs, the fuel injection quantities is increased from 13.153mg/pulse to 22.080mg/pulse, of which the variation is very small at above sampling engine speeds, however the operating frequency of the H.P. fuel injector is closed to 75 pulses /s (corresponding to engine speed at 9000 RPM), inadequate fuel injection quantities would begin to result in significant fuel variations exceeding 1600μs pulse duration.

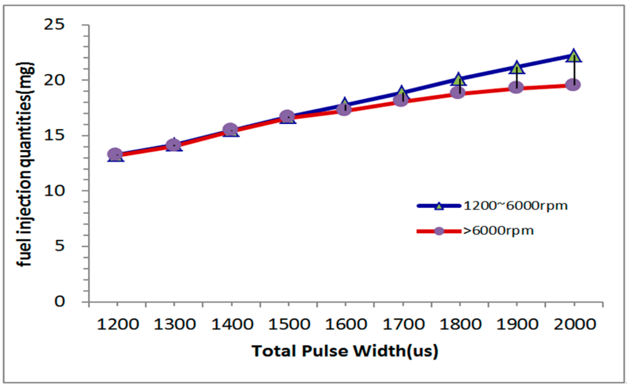

Fig. 8 Effect of various speeds and pulse widths on the fuel injection quantities of the GDI injector fed by the three-pulse driving current

4.2 Effect of Injector's Supply Voltage and PWM Operation

In the practical electrical circuits of motorcycle GDI engines, the injector's supply voltage drop significantly influences the fuel injection quantities during high speed injecting operation. Effect of the injector's supply voltage and PWM control on the fuel injection quantities is required to investigate in the fuel injection experiments. An injecting pulse signal from ECU is fed into the three-stage power MOSFETs PCB to generate the three-stage (12/5/3A) current waveforms. The three-stage currents are supplied to drive the actuators in the H.P. fuel injector. In the experiments, the driver supply voltage is varied from 40 to 70 volts and the pressure of the fuel supply system is set at 100 bars. A power MOSFETs-switch H.P. driver is designed with a wide range of injection pulse durations (1200~2000μs). The fuel injection quantities for three engine speed settings at 1200rpm, 2400rpm, and 6000rpm are measured. The DC supply voltage is supplied to drive the actuators in the H.P. fuel injector for carrying out the fuel injection experiments. In the research, the effects of the injector supply voltage on the fuel injection quantities of the H.P. fuel injector fed by the three-stage 12/5/2.5A (without PWM mode) and 12/5/3A driving current (with PWM mode) are investigated. The pressure of the fuel supply system is set at 100 bars. An injecting pulse duration (1500μs) is sent to the three-stage power MOSFETs H.P. driver to measure the fuel injection quantities for three engine speed settings

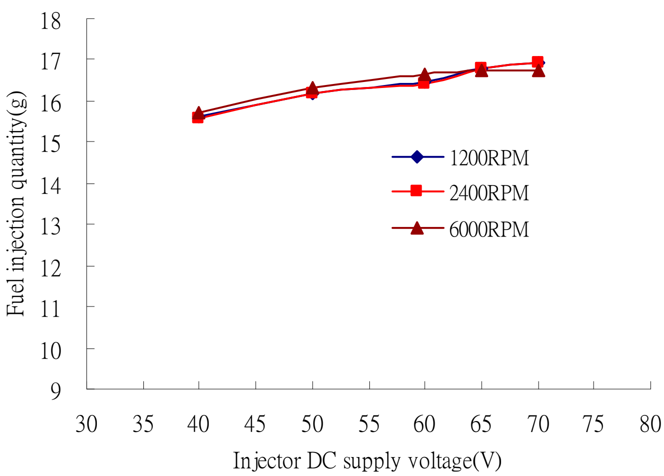

Fig. 9(a) Effect of the injector supply voltages on the fuel injection quantities of the H.P. injector (PWM control withdrawn from the last pulse duration)

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at 1200rpm, 2400rpm, and 6000rpm. Effect of the injector supply voltages on the fuel injection quantities of the H.P. fuel injector without PWM control added to the 2.5A holding currents during last pulse duration is presented in Fig. 9(a). In Fig. 9(a), the fuel injection quantities fed by the DC 40V injector supply voltage are 15.641g, 15.568g and 15.729g at 1200rpm, 2400rpm and 6000rpm respectively. They are almost same and irrespective of engine speeds. When the injector supply voltage is raised to DC 70V, the fuel injection quantities increased to 16.935g from 15.641g. The equations for characterizing the fuel injection curves are given by:

$m_{fuel} = -0.0003V_s^2 + 0.0736\ V_s + 13.175$ (R2 =0.9992) between 1200 and 6000 rpm

$m_{fuel} = -0.0013V_s^2 + 0.1773\ V_s + 10.722$ (R2 =0.9994) for exceeding 6000 rpm (11)

where m_{fuel}= fuel injection mass (mg/pulse); V_s= power supply voltage (V)

Also, PWM control is added to the 2.5A holding currents during the last pulse operation as shown in Fig. 9(b). It is shown from these results that the fuel injection quantities are varied with the injector supply voltage. However, the fuel injection quantities fed by the DC 40V injector supply voltage shows 9.314g, 9.328g and 9.952g at 1200rpm, 2400rpm and 6000rpm respectively (Fig. 9(b)). When the injector supply voltage is raised to DC 70V, the fuel injection quantities increased to 15.327 from 9.314g in the case of 1200rpm engine speed. As the fuel injection quantities are decreased to 9.314g as a result of the addition of PWM control to the 2.5A holding currents during the last pulse duration, variations of the fuel injection quantities among engine speeds became less and more stable due to PWM control operation added to the 2.5 A holding currents during last pulse durations. The following characteristic equations for the fuel injection curves can thus be obtained:

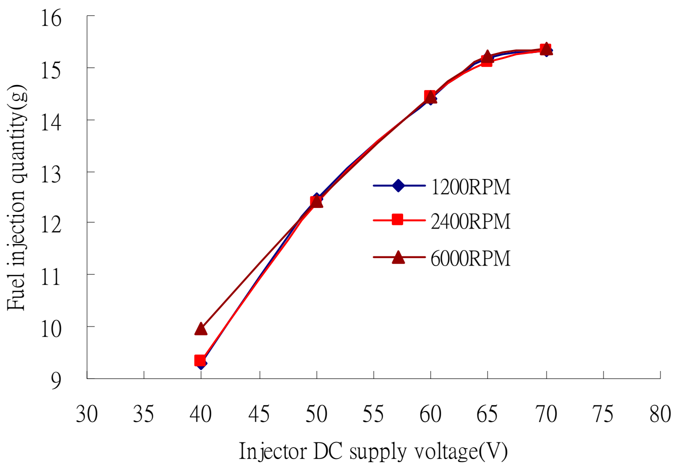

Fig. 9(b) Effect of the injector supply voltages on the fuel injection quantities of the H.P. injector (PWM control added to the last pulse duration)

$m_{fuel} = -3E\text{-}05V_s^3 - 0.0003V_s^2 + 0.5339\ V_s - 9.4735$ from 1200rpm to 6000rpm (R_2 =0.9991)

$m_{fuel} = -0.0001V_s^3 + 0.0179V_s^2 - 0.5583\ V_s + 12.136$ for exceeding 6000 rpm (R_2 =0.9991) (12)

where m_{fuel}= Fuel injection mass (mg/pulse); V_s= power supply voltage (V)

It is shown from these test results addition of last pulse PWM control to the H.P. fuel injector driving circuits improves the injector's performance and provides a more stable and accurate fuel injection quantities of the H.P. fuel injector in the fuel supply and injection system at an operating voltage range between DC 60 and 70V. Therefore, it is required to design a voltage booster circuit in order to improve the power supply voltage operating in excess of DC 60V as well as adding PWM control to the 3A holding current during last pulse durations in the further investigations.

4.3 Effect of Fuel Pressure and PWM Operation

The fuel and the fuel pressure of the H.P. fuel injectors is supplied by a high-pressure fuel pump, which have to be large enough to supply more fuel than the maximum amount that the engine may require to ensure that the fuel pressure remains adequate at full throttle and at maximum RPM. The fuel pressure supplied by the fuel pump of motorcycle GDI engines is usually dipped and the pressure significantly influences the opening time and the fuel injection quantities of the H.P. fuel injector under the engine operating with high speed or heavy load. It is essential to investigate the fuel injection quantities of the H.P. fuel injector at the various fuel supply pressures. The fuel injection quantities between two current operating modes and various fuel pressures at the engine speed 6000rpm is compared in Figs. 10(a) and 10(b). Basically, during the testing of fuel injection quantities of the H.P. fuel injector, the electrical driving circuit is designed to supply a three-stage (12/5/3A) current waveform to the injector coils in order to generate the electromagnetic force to

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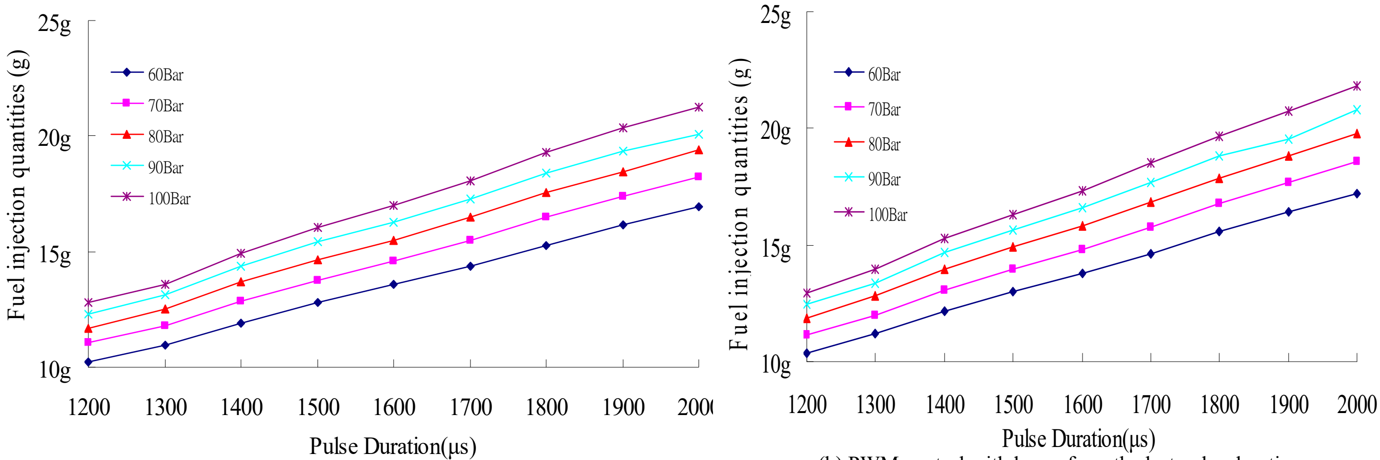
draw back and hold the nozzle needle of the injector. At the various fuel pressures ranging from 60 to 100 bars, the fuel injection quantities with and without PWM control added to the last holding pulse are obtained in Fig. 10(a) and 10(b). From the results in Fig. 10, the PWM control provides the injector with a faster closure and a higher response performance. The equations for characterizing the fuel injection curves without PWM control added to the injector driving circuit can be written as:

$m_{fuel} = 1.114\ t_p + 11.826$ for 100 bars
$m_{fuel} = 1.038\ t_p + 11.429$ for 90bars
$m_{fuel} = 0.994\ t_p + 10.879$ for 80bars
$m_{fuel} = 0.932\ t_p + 10.195$ for 70bars
$m_{fuel} = 0.852\ t_p + 9.5241$ for 60bar (R2 =0.9988) (13)



(a) PWM control added to the last pulse duration (b) PWM control withdrawn from the last pulse duration

Fig. 10 Comparison of the fuel injection quantities (a) with and (b) without PWM control at various fuel pressures at engine speed 6000rpm

The equations characterizing the fuel injection curves for PWM control adding to the injector driving circuit are also obtained as follows:

$m_{fuel} = 1.0827\ t_p + 11.621$ for 100bar
$m_{fuel} = 0.9965\ t_p + 11.297$ for 90bar
$m_{fuel} = 0.9726\ t_p + 10.681$ for 80bar
$m_{fuel} = 0.9067\ t_p + 10.089$ for 70bar
$m_{fuel} = 0.8438\ t_p + 9.3587$ for 60bar (R2 =0.9985) (14)

where m_{fuel}= Fuel injection mass (g); t_p= pulse duration (μ)

4.4 Effect of First-Stage Turn-on Pulse Width

In order to understand the effects of the first-stage turn-on pulse width on the fuel injection quantities, the total driving pulse duration is adjusted between intervals of 1200~2000μs, the injector voltage is supplied by DC 60V and the pressure of the fuel supply system is set at 100 bar as the experimental conditions. The first-stage turn-on driving pulses are set at 180μs and 200μs to generate the 10A and 12A driving currents respectively. The peak charging current amplitude during the first-stage turn-on pulse duration is interrelated to the fuel injection quantities. As for the case of 200μs first driving pulse width in Fig. 7, the driving pulse width is adequate to

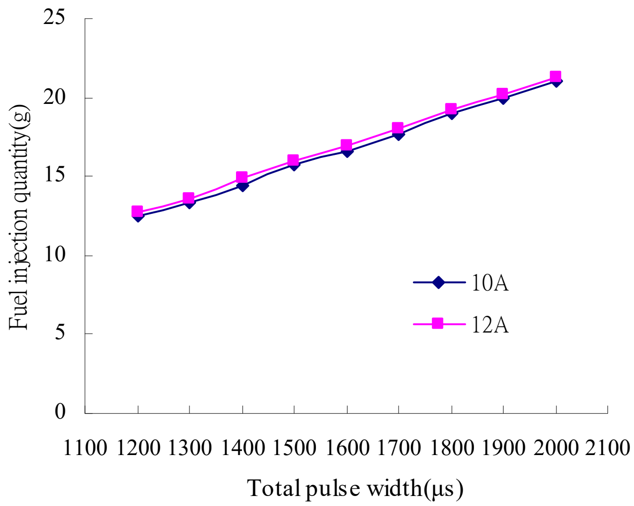


Fig. 11 Comparisons between 10 and 12A peak driving currents on fuel injection quantities at 6000rpm

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boost the first-stage H.P. fuel injector peak current to 12A. The H.P. fuel injector peak current is able to fully draw back the needle of the H.P. fuel injector and thus yielding the stable fuel injection quantities. The effects of the first-stage turn-on 10A and 12A driving currents on the fuel injection quantities of the H.P. fuel injector are investigated and discussed in Table 3. It is noticed in the table that the variations in the fuel injection quantities are changed from negative to positive in comparison between the 10A and 12A first-stage turn-on driving currents at the engine speed 9000rpm. At this engine speed, the 10A first-stage turn-on driving current causes a reduction in the injector supply voltage drop and hence, resulted in more fuel quantity squirted. At the pulse intervals ranging from 1200~2000μs, the fuel injection quantities are increased to 20.998g from 12.452g and to 21.325g from 12.733g for the cases of the 10A and 12A driving currents respectively. The 12A fuel injection quantities are slightly more than those of the 10A first-stage turn-on driving current as shown in Fig. 11. The fuel injection quantities can be derived by the following equation for characterizing the fuel injection curves:

$m_{fuel\_12A} = 1.0868\, t_p - 11.56$ for all engine speeds (R2 =0.9991)

$m_{fuel\_10A} = 1.0868\, t_p - 11.24$ for all engine speeds (R_2 =0.9989) (15)

where m_{fuel}= Fuel injection mass (g); t_p= pulse duration (μs)

Therefore, the more favorable first-stage turn-on driving currents are ranged between 12 and 10A for the H.P. fuel injector characteristics.

5. Conclusions

The injector driving circuit has been developed for the high-pressure (H.P.) injector in order to achieve rapid response and good air-fuel ratio control for GDI engines. As it can be seen from the results, an injector drive circuit was developed to improve the fuel injection of H.P. fuel injector reducing the lifetime of solenoid coils of an injector actuator during the fuel injection operation. PWM control was added to the power MOSFET drive circuit to quickly turn off the H.P. fuel injector injection. The injector drive circuit has been successfully implemented in many high-speed and long-lasting fuel injection experiments to verify its feasibility, meeting the operating characteristics of H.P. syringe. In this paper, experimental studies have been conducted to characterize the fuel injection curve of the H.P. fuel injector. Based on the operating requirements of the GDI fuel injector, an adjustable injector driving circuit was developed using a reference current profile. The GDI injector was calibrated by the injector driving circuit to improve the stability of automotive engines during their operation. Experimental investigations were used to characterize the performance of the injector driving circuit. Some main conclusions have been drawn:

Table 3 Comparisons between 10 and 12A peak driving currents on fuel injection quantities

Pulse Width	rpm	10A	12A	**variation**
1200μs	1200	12.452	12.733	**-0.281**
	2400	12.515	12.768	**-0.253**
	6000	12.529	12.739	**-0.210**
	9000	12.596	12.513	**0.083**
1300μs	1200	13.288	13.566	**-0.278**
	2400	13.411	13.607	**-0.196**
	6000	13.384	13.602	**-0.218**
	9000	13.427	13.343	**0.084**
1400μs	1200	14.402	14.866	**-0.464**
	2400	14.489	14.883	**-0.394**
	6000	14.549	14.925	**-0.376**
	9000	14.591	14.613	**0.122**
1500μs	1200	15.716	16.001	**-0.285**
	2400	15.838	16.042	**-0.204**
	6000	15.893	16.098	**-0.205**
	9000	15.914	15.758	**0.156**
1600μs	1200	16.639	16.931	**-0.292**
	2400	16.753	17.298	**-0.545**
	6000	16.818	17.036	**-0.218**
	9000	16.844	16.691	**0.153**
1700μs	1200	17.671	18.023	**-0.352**
	2400	17.802	18.237	**-0.435**
	6000	17.888	18.188	**-0.300**
	9000	17.924	17.773	**0.151**
1800μs	1200	18.939	19.254	**-0.315**
	2400	19.06	19.308	**-0.248**
	6000	19.172	19.426	**-0.254**
	9000	19.198	18.972	**0.226**
1900μs	1200	19.952	20.246	**-0.294**
	2400	20.102	20.444	**-0.342**
	6000	20.219	20.428	**-0.209**
	9000	20.238	19.956	**0.282**
2000μs	1200	20.998	21.325	**-0.327**
	2400	21.156	21.342	**-0.186**
	6000	21.279	21.509	**-0.230**
	9000	21.308	20.991	**0.317**

1. The designed injection system can be applied in other engines; however, it is required to investigate the classifications of the combustion system equipped in the GDI engine before the experiment. The GDI combustion system can be assigned to one of these major classifications: spray-guided, wall-guided and air-guided, on the basis of strategies for realizing stratified charge operation during part load. It is essential to

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select a high-pressure injector that is appropriate for the performance of the tested engine combustion system. An experimental investigation on the characterization of the dynamic performance for the selected high-pressure injector is implemented in the paper by the design of injector driving circuit, injector experimental procedures, and the derived fuel injection curves using polynomial curve fitting method.

2. The designed GDI injector driving circuit improves the injector's performance and provides more stable and accurate fuel injection quantities in the H.P. fuel injecting system. The power supply voltage of the H.P. fuel injector has to be operated and held in excess of DC 60V to squirt adequate fuel quantities, otherwise the 500c.c. motorcycle GDI engine would run a transition from homogeneous combustion to lean burn combustion even misfire.
3. The H.P. fuel supply system for GDI engines is capable of operating stably and assuring the accurate injection quantities to precisely control the superior performance of GDI engines under the influence of the three-pulse power drive circuit. The developed injector drive circuit is implemented well in both experiments and practical applications. The self-tuning algorithm can optimize the driving parameters in the GDI Engine. It ensures the repeatability and stability of the injection. The experimental injection quantity curves for the injector driving circuit need to be properly configured to ensure the injection quality. Therefore, the fast response and superior performance would be achieved in automotive GDI engines by the well-designed injector drive circuit.

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Author Contributions: The author proposed to design a new electrical driving circuit for the H.P. GDI injector. The designed electric driving circuit is tested to verify its feasibility and performed. The author carried out the driving circuit allows the H.P. fuel supply system its ability to operate stably and assures accurate fuel injection quantities to precisely control the expected AFR in the 500 c.c. motorcycle GDI engine operation. Design and analysis of the proposed injector drive circuit are presented. Next, effects of total pulse width, injector supply voltage, fuel system pressure and PWM operation on fuel injection quantities of a H.P. fuel injector are measured. Also, the measured data of the H.P. fuel injector fed by the injector driving circuit are defined as the fuel injection curves. Finally experimental results are provided for verification of the proposed injector drive circuit. The author also drafted the manuscript.

Conflicts of Interest: The author declares no conflict of interest.

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