DESIGNING A PROTOTYPE LPG INJECTION ELECTRONIC CONTROL UNIT FOR A CARBURETTED GASOLINE ENGINE

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Abstract: In this study, the originally carburetted gasoline engine was converted to gas-phase liquefied petroleum gas (LPG) injection engine by using an aftermarket LPG conversion kit's components except the electronic control unit (ECU). Instead of aftermarket LPG injection ECU, the ECU which was designed considering the effects of electromagnetic interference (EMI), was used for controlling injection. Designed ECU was used in performance tests at different engine conditions and the results obtained with LPG injection were compared with the results obtained with LPG carburetion. According to the performance test results, LPG injection ECU designed in this study could help to achieve low exhaust emissions and high engine performance.

Keywords: LPG injection, electronic control unit, electromagnetic interference, noise suppression methods.

Karbüratörlü Bir Benzin Motoru İçin LPG Püskürtme Elektronik Kontrol Ünitesi Tasarımı

Özet: Bu çalışmada, orijinali karbüratörlü benzinli olan bir motor, elektronik kontrol ünitesi hariç olmak üzere piyasada bulunan LPG dönüşüm kiti bileşenleri kullanılarak gaz fazında LPG' nin püskürtüldüğü bir motor haline dönüştürülmüştür. Dönüşüm sisteminin bir bileşeni olan LPG püskürtme elektronik kontrol ünitesi yerine, püskürtme işleminin kontrol edilmesi amacıyla elektromanyetik girişim etkilerinin dikkate alındığı yeni bir elektronik kontrol ünitesi tasarlanmıştır. Farklı motor şartlarında gerçekleştirilen performans testlerinde tasarlanan elektronik kontrol ünitesi kullanılmış ve LPG püskürtme sistemi ile elde edilmiş sonuçlar, karbüratörlü LPG sistemi ile elde edilen sonuçlar ile karşılaştırılmıştır. Performans test sonuçlarına göre bu çalışmada tasarlanan LPG püskürtme elektronik kontrol ünitesi düşük egzoz emisyonları ve yüksek motor performansı değerlerinin elde edilmesine yardımcı olmuştur.

Anahtar Kelimeler: LPG püskürtme, elektronik kontrol ünitesi, elektromanyetik girişim, gürültü bastırma metotları.

1. INTRODUCTION

Environmental pollution and energy shortages have become increasingly important worldwide concerns (Wang et. al., 2009). LPG is widely used as a gaseous fuel in spark ignition (SI) engines because of its considerable advantages over gasoline (Hansub et. al., 2005). But first

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generation LPG fuel systems are the simplest forms of LPG conversion systems and are ordinary in countries where vehicles are not required to meet stringent emission standards (Biscoff et. al., 2012). Torque loss is another problem because the vapour-phase LPG displaces a larger volume of air than do gasoline droplets and in order to improve engine power as well as fuel consumption and air/fuel ratio control, considerable research has been devoted (Hansub et. al., 2005).

The development of mechatronic systems influences the design, functions and manufacturing of many products in the areas of machines, vehicles and precision mechanics (Isermann, 2008). Internal combustion (IC) engines have been introduced as mechatronic systems. A synergetic integration of the different disciplines allows an intelligent design of new engine control strategies (Hafner et. al., 2002). In the recent past and in the foreseeable future, most innovations in automotive systems rely on electronics (Schöner, 2004). Studies which are given below, are about the development of electronically controlled gaseous fuel injection systems in literature, can be given as examples for mentioned integrations. A compressed natural gas (CNG) injection ECU was designed on the basis of circuit simulation and modelling by Wang et. al. (2009). The ECU which was built by using 32-bit microcontroller MPC561, was applied on a real CNG engine bench. The functions of hardware and software were verified in bench tests. The power and torque performances of the CNG engine were very close to the design targets, and the emissions of the CNG engine were low. Loganathan and Ramesh (2007) developed a LPG injection ECU by using mono-stable multi-vibrator based electronic circuit. Crankshaft position sensor was used to trigger the ECU. The timing and duration of injection were set by using potentiometers. According to this study; though there was a significant difference between LPG carburetion and injection the difference was not very significant between gasoline and LPG injection in terms of performance and emissions. Another study about designing LPG injection ECU was done by Sunwoo et al. (1999). ECU was developed by using Motorola microcontroller unit (MCU) MC68HC05 and the experimental results showed that the prototype ECU and its control scheme provided the superior engine performance in terms of idle stability and emission reduction. Campbell et al. (2003) designed a LPG fuel injection system which was for fuelling the 4th cylinder of 4-cylinder multipoint injection engine, was built by using a 555 based timer circuit and finally it was found that the performance loss due to using vaporised LPG fuel compared to gasoline was of the order of 10% to 20%. Li et al. (2003) obtained better HC, NOx and CO emissions with electronically controlled LPG gas injection system developed in their study, compared to the LPG mechanical mixer system.

LPG systems which inject the LPG into the inlet port in the liquid state rather than as a gas, improve the volumetric efficiency (Campbell et. al. 2003). A multi-point liquid LPG fuel injection system was developed by Sierens (1992), in cooperation with the Dutch company Gentec. The injection which was dependant on the engine speed, was started before the opening of the inlet valve. According to this study; at a same air/fuel ratio both gasoline and liquid LPG injection systems gave nearly exact the same power output. Another study about the liquid LPG injection was presented by Watson and Phuong (2007). Instead of designing a new injection control unit, an aftermarket ECU (MOTEC M4) was used in this study. According to this study; the experimental data confirmed the power and efficiency advantages of liquid phase injection over gas phase injection and carburetion in multi-cylinder engine tests.

LPG injection techniques influence the engine performance. The effects of simultaneous and sequential injection methods of vaporized LPG on engine performance were investigated by Wendeker et al. (2007). Engine was controlled by using universal engine controller AMX 200 CAN. According to this study; the changing of injection style from simultaneous to sequential in case of engine fuelled with stoichiometric mixture did not result in significant changes of mean indicated pressure and delivered torque. On the other hand, higher torque and mean indicated pressure values were obtained with simultaneous injection method compared to sequential injection method at excess air ratio of 1,2.

Most of the studies about the effects of LPG injection systems on exhaust emissions and engine performance were performed by using aftermarket LPG conversion kits without any design purpose in literature. A small number of studies include designing LPG injection control units and there is very little information about the design considerations such as electromagnetic noise suppression methods. In recent years, millions of microcontrollers have been used in the automotive field and there are hundreds of microcontrollers in a modern car (Wan et. al., 2012). Problems related to electro-magnetic compatibility (EMC) and EMI become more complex and difficult than that in the past and in ECUs on which microcontrollers are equipped, electromagnetic radiation causes EMI and can be emitted efficiently when conductor patterns of printed circuit boards (PCBs) and wire-harnesses act like antennas (Mabuchi et. al., 2009) so EMI becomes a great concern to deal with, in every kind of application and especially in power electronics (Serrao et. al., 2008). To present the designed prototype gas-phase LPG injection ECU with detailed information about EMI and to investigate the effects of control unit on engine performance are the main objectives of this study.

2. THE HARDWARE OF LPG INJECTION ELECTRONIC CONTROL UNIT

The detailed descriptions about the subsystems and design considerations of injection electronic control unit hardware are given below.

2.1. Power-supply unit

The purpose of the dc power-supply unit is to provide positive (VDD) and negative 5V voltages to the ECU by using LM7805 three terminal positive voltage regulator and MAX764 inverting switching regulator. The input voltage for the both regulators is the battery voltage of 12V. Digital integrated circuits (IC's) use dc power supplies, and the dc current on the digital IC's power supply terminal will be interrupted according to the IC operation. Such a sporadic change in current causes EMI noise (Murata, 2012). Ideally a power-supply is a zero impedance source of voltage but unfortunately practical supplies do not have zero impedance so they represent a source of coupling between the circuits using them and it is a good practise to provide some decoupling at each circuit or group of circuits to minimize noise coupling through the supply system (Ott, 1988). In this study, inductor-capacitor decoupling networks were used instead of resistor-capacitor networks, since inductor-capacitor filter provides more filtering than the resistor-capacitor filter for the same loss in power-supply voltage. The resonance frequencies of filters are well below the pass bands of the circuits connected to the filters and the damping factors of filters are greater than 0,5 to limit the gains at resonance frequencies. Inductor-capacitor filters used in this study, were T-type since T-type LC filters provide greatly improved stop-band attenuation compared to the Pi-type filter (Chipcon, 2003).

2.2. Micro controller unit

The ECU was designed by using a Microchip MCU 16F877A as shown in Figure 1. Real time information about engine speed and the positions of crankshaft and throttle are received and then injection is performed by MCU according to the embedded code. In order to supply the stable current needed by MCU, decoupling capacitor was used between power-supply and ground pins, as close to the chip as possible, so the load on the power lines was reduced and unwanted glitches were removed as possible in the power system (Freescale, 1995).

2.3. Isolation circuits

Ground loops can be a source of noise. If a system is grounded at two different points with a potential difference between the grounds, this can cause an unwanted noise voltage in the circuits.

In order to solve this problem, optically coupled isolator circuits were used to break the ground loops between the circuits.
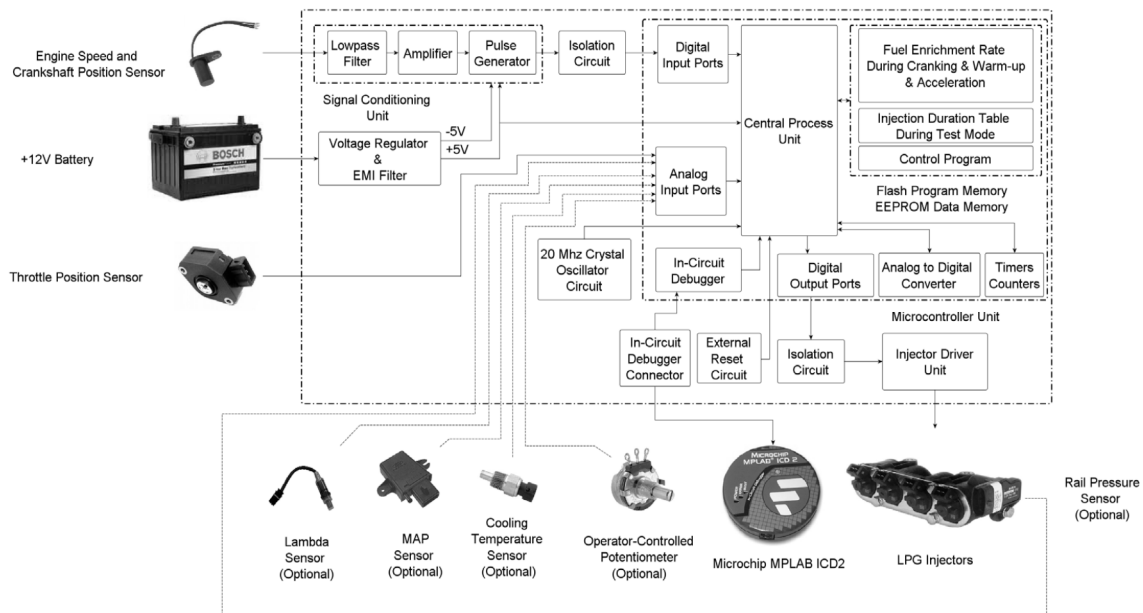

Figure 1:
Block diagram of electronic control unit.

2.4. Injector driver unit

If an inductive load such as an injector is controlled by a transistor or mosfet switch, care must be taken to guarantee that the transient voltage generated by the inductor when the current is interrupted does not exceed the breakdown voltage of transistor or mosfet. One of the most effective, and common, ways to do this is to place a diode across the inductor (Ott, 1988). LPG injectors are triggered by power mosfets so snubber diodes were used to eliminate the sudden voltage spikes seen across the injectors.

2.5. Inductive sensor output signal processing unit

Engine speed and crankshaft position parameters are obtained by signal processing unit. Magneti Marelli SEN8M inductive sensor was used to obtain the speed and position. The sensor output is proportional to the engine speed so output voltage level increases by increasing the engine speed. The output voltage is approximately between 2V and 12V throughout the speed range. In order to obtain suitable voltage levels for MCU such as logic one or logic zero, a signal processing unit included passive low pass RC filters and operational amplifiers, was used.

2.6. Grounding and shielding

Grounding is one of the primary ways of minimizing unwanted noise and pickup. Proper use of grounding and cabling, in combination, can solve a large percentage of all noise problems (Ott, 1988). Injection control unit has four separate ground returns such as analog signal ground used for analog electronic circuits, digital signal ground used for digital electronic circuits, noisy ground used for injector driver unit and hardware ground used for chassis. The four separate ground return circuits were connected at one point which was power-supply and this point was a ground for the shields of signal cables also. Each of separated ground returns have as small as possible ground impedance. In order to prevent noise interference between circuit blocks, the

ground impedance was reduced by making the ground pattern short and wide between the circuit's input and output. An eddy current engine dynamometer was used in the tests so there were very strong electromagnetic fields around the brake. To minimize the effects of electromagnetic fields on circuits, system components were placed in a grounded iron box which did not have any hole on the surfaces. Furthermore all the signal cables were shielded and the shields were grounded at both ends of cables so the whole control system was insulated from any electromagnetic field.

2.7. Signal patterns on the printed circuit boards

Even if a circuit is designed for a similar operation, the radiated noise level varies depending on the component or pattern layout on the PCB. The radiated noises were suppressed as possible by reduced both the length-width of transmission lines and the gaps between the ground patterns and the signal patterns (Murata, 2012). In addition to these measurements, 45^0 angle signal trace turns instead of 90^0 angle signal trace turns were used to decrease transmission reflections and the circuits on PCB were separated according to their frequency and current switching levels (Freescale, 1995).

3. INJECTION CONTROL PROGRAM

In order to establish a preliminary fuel injection look-up table, dual fuelled Renault Clio vehicle powered by a 1,4 litre multi-point gasoline engine, was used. Gasoline and LPG injection durations were obtained in road tests by using an interface software of LPG kit for different engine operating modes such as engine crank, warm-up, open-loop control, closed loop control, acceleration, deceleration and idle. The results obtained from 1,4 litre engine were interpolated to establish the injection look up table for 1,6 litre engine. After these interpolations, preliminary fuel injection look-up table was established for the test engine and then this look-up table was embedded to the designed ECU. Embedded look-up table was calibrated to reach the stable engine running under almost all test conditions on engine dynamometer so a base injection duration map which could run the engine in every situation, was obtained without considering the performance, emissions and efficiency. After this first calibration process, the base injection duration map was calibrated again by considering the performance, emissions and efficiency at each step of performance tests planned for open-loop mode at desired air/fuel ratios so the final injection duration maps were obtained for using at planned performance tests. If additional calibrations are desired on the cells of final injection maps, an operator-controlled potentiometer can be added to system so the duty cycles of injection control signals can be changed by considering the output signal levels of potentiometer.

Four of different prior engine operating modes (engine crank, warm-up, open-loop control and acceleration) which affects the fuel control, were considered in injection control program. The control system determines the operating mode from the existing sensor data and calls the particular corresponding program routine. Deceleration and idle speed control modes were not considered since the performance tests were carried out between 2000 and 4000 rpm engine speeds with intervals of 500 rpm, at fixed throttle positions of 25% and 50% of full opening. In addition to these not considered modes, closed-loop control mode was not taken into account also since it was desired that the controlling of injection duration was performed by manual interventions.

Improving the fuel consumption was beyond the scope of this study during the cranking, warm-up and acceleration modes so the excess air ratio values were adjusted to an approximate average value of 0,63 which was rich enough for these modes without any unstable engine running conditions. But if required, these same values can be adjusted to the different values by changing the injection durations in existing look up table. While the engine is being cranked, the fuel control system must provide an intake air/fuel ratio of anywhere from 2:1 to 12:1, depending on engine temperature (Ribbens, 2003). The primary issue is to achieve the starting of engine as rapidly as

possible during the cranking. The cranking mode is valid between 150 rpm and 350 rpm engine speeds but if required, the limit of the speed interval can be adjusted to the another value by changing the existing code. Once the engine is started, the controller switches to engine warm-up mode. The cooling temperature output signal is not an input parameter for injection control unit since the injection control unit was designed for only using in performance tests at cooling temperature of around 81 ^{0}C. Operator observes the cooling temperature by using dynamometer control program and waits for starting the performance tests until the cooling temperature reaches to 81 ^{0}C at a constant throttle position. The discrimination between warm-up and open-loop control is performed by using engine speed at a constant throttle position. Operator should not keep the engine in open-loop test mode at lower engine speeds than 1000 rpm which is accepted as upper limit for warm-up mode by the injection control program. But the limit of the warm-up mode can be associated with cooling temperature by adding a temperature sensor to the hardware so the mixture enrichment ratio can be adjusted during warm-up period by a look-up table added to the code. After warm-up period, if the performance tests are started, engine becomes in acceleration mode since the throttle position is adjusted from closed position to required value automatically by the dynamometer control program. Microcontroller detects the acceleration mode by obtaining the throttle angle sensor voltage. High throttle angle is an indication that acceleration period and the pulse durations of the fuel injector signals are increased by the microcontroller. After the acceleration, engine reaches to stable running conditions at required engine speed and throttle position that can be called as a test point and engine is in open-loop mode. The excess air ratio can be adjusted to a desired value for each test step by previously prepared injection look-up tables. A double-stage simultaneous injection strategy is applied in all engine modes because half of the cyclic fuel quantity is injected during each half of the cycle (Erkuş et. al., 2013). The fuel consumption and excess air ratio values obtained during open-loop tests with LPG injection are shown in Table 1.

Table 1. Fuel consumptions and excess air coefficients during open-loop tests.

Engine Speed (rpm)	25% Throttle Position		50% Throttle Position	
	Fuel Consumption (g/sec)	Excess Air Ratio	Fuel Consumption (g/sec)	Excess Air Ratio
2000	1,39	0,98	1,58	0,95
2500	1,75	0,98	1,83	1,02
3000	1,96	1,01	2,26	1,00
3500	2,38	1,00	2,81	0,96
4000	2,23	0,95	3,09	1,03

Engine speed and piston position parameters are obtained from the pins placed to the flywheel of test engine (Figure 2.) by using an inductive sensor. According to Figure 2; 1st pin represent the top dead centers (TDCs) of 1st and 4th cylinders. 2nd pin which is placed 9^0 crank angle (CA) before from the 1st pin, is used to differentiate the TDCs of 1st and 4th cylinders from the TDCs of 2nd and 3rd cylinders. 2nd, 3rd, 4th and 5th pins were placed on flywheel with intervals of 90^0 CA from each other. The elapsed times between the detection of 4th - 3rd pins and 2nd - 5th pins are used for calculation of the engine speeds. Injection processes are performed in the time intervals between the detection of 5th - 4th pins and 3rd - 2nd pins.
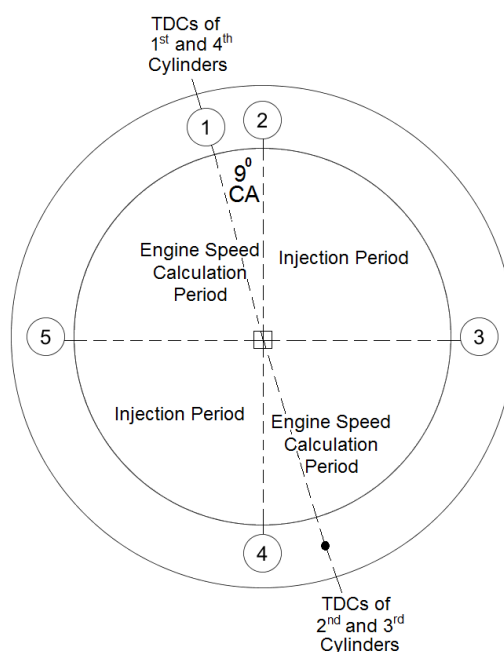
Figure 2:
Flywheel of test engine.

The codes of injection control program was written by using C and assembly programming languages. The flowchart of embedded codes to the ECU is shown in Figure 3. Initially, ECU calculates the engine speed by using the 16 bits timer. The 90^0 CA rotation of the flywheel is used for calculation in order to avoid the overflow of timer registers. If the engine speed is not enough for cranking, ECU will be reset by the program. When the engine speed is higher than 150 rpm, 2nd and 1st pins are detected to obtain the TDCs of 1st and 4th cylinders by using the elapsed time during 9^0 CA rotation of flywheel and then 5th, 4th and 3rd pins are detected respectively. After detecting the 3rd pin, program enters into an infinite loop (A) and the throttle position information is obtained at the start of each cycle by analogue digital conversion of throttle position sensor's output signal. Although there is not any remarkable difference between the throttle positions except acceleration mode, program calculates the difference between the throttle positions. If the difference between throttle positions is higher than approximately a value of $0,44^0$ (If required, the value of $0,44^0$ can be adjusted to another value by simple modification on existing code.), it is accepted that the engine is in acceleration mode. If the difference is not higher than $0,44^0$, engine is in one of the modes of cranking, warm-up or open loop test according to engine speed. There is another loop (B) in the loop A. The loop count of B loop is adjusted as two since one engine cycle is completed after the flywheel rotates 720^0 CA. When the loop count is one; the engine speed is calculated from the elapsed time between the detection of 2nd and 5th pins. According to engine speed and throttle position difference, the injection process which has to be finished until detecting the 4th pin, is started. After the first injection process is finished, the engine speed is calculated again from the elapsed time between the detection of 4th and 3rd pins. According to engine speed and throttle position difference, the injection process which has to be finished until detecting the 2nd pin, is started and thus injection processes are performed twice during 360^0 rotation of flywheel. When the loop count is two, the processes mentioned above are repeated so one cycle or in other words the execution of loop B is finished. Then the execution of program continues in loop A and the throttle position information is obtained again at the start of cycle and the execution of loop B is started.
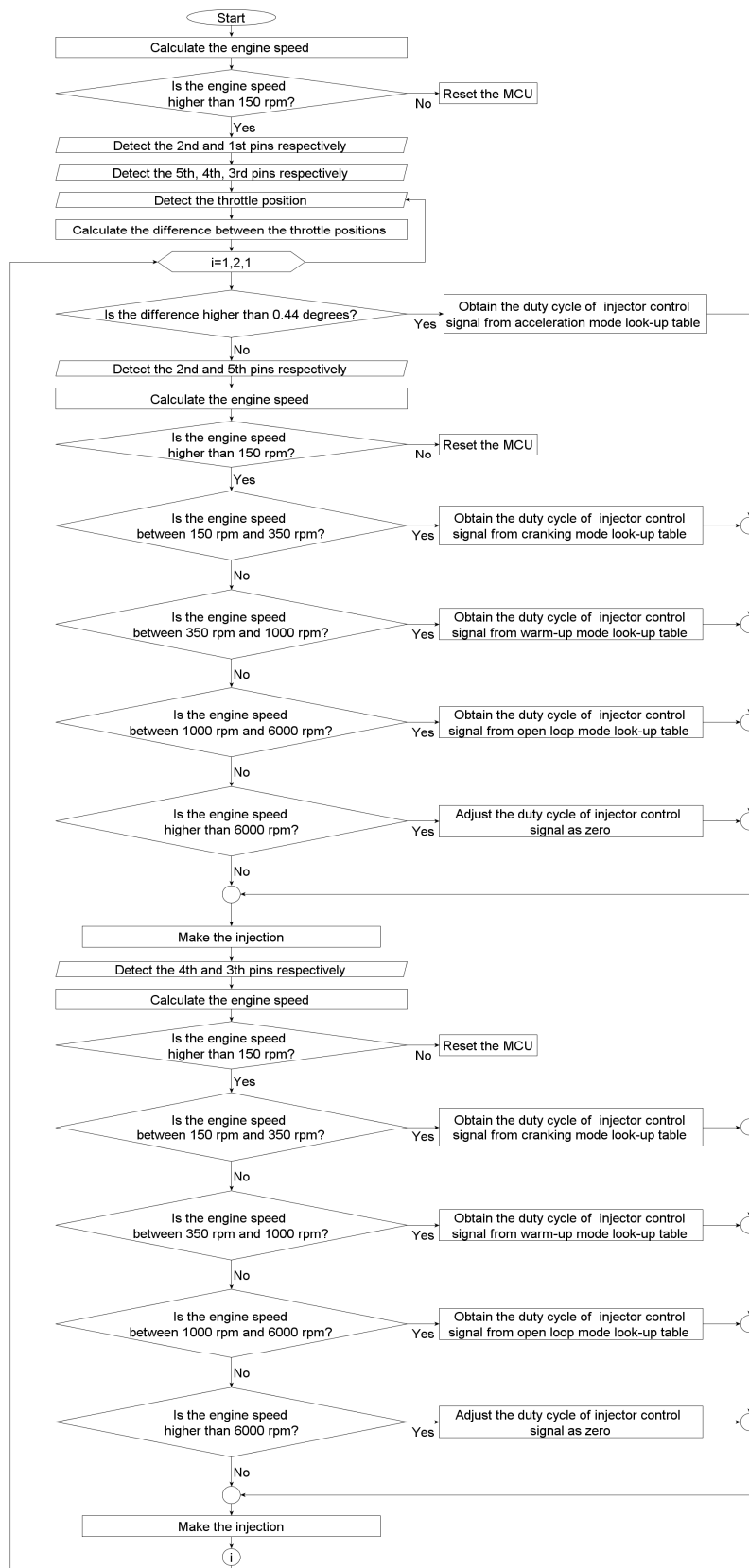
Figure 3:
Flow chart of embedded program to the ECU.

The fluctuations on engine speed are monitored permanently by the program and if the engine speed drops below the pre-set value of 600 rpm during the execution of program, program resets the ECU. If required, the value of 600 rpm can be adjusted to another value by simple modification on existing code. If cranking is achieved and the engine speed does not drop below the pre-set value, program continues to run the engine. The maximum engine speed was limited to 6000 rpm by the program for safety reasons.

4. THE DETAILS OF TESTS

In order to make a comparison between LPG carburetion and injection; performance tests were carried out with LPG mechanical mixer system firstly and then the originally carburetted gasoline engine whose specifications are listed in Table 2, was converted to gas-phase LPG injection engine so the effects of designed LPG injection ECU on engine performance and exhaust emissions could be obtained. All of the components of the LPG injection system, except the ECU, were obtained from an aftermarket LPG conversion kit manufactured by a domestic firm (VIKARS).

Table 2. Specifications of the test engine.

Type	Four stroke, SI
Numbers of cylinders	4
Swept volume	1581 cc
Maximum brake power	64,1 kW at 5800 rpm
Maximum brake torque	130 Nm at 2900 rpm
Brake torque at 5800 rpm	105,6 Nm
Compression ratio	9,2:1
Cooling system	Water cooled

The LPG utilized in the engine tests consists of 30% propane and 70% butane. Physical and chemical properties of the propane, butane and gasoline fuels are listed in Table 3 (Gumus and Ugurlu 2011). LPG consumption was measured using a highly sensitive digital weighing machine.

An eddy current engine dynamometer with maximum absorption power of 185 kW and a maximum speed of 7000 rpm was connected to the flywheel of the engine to control its speed and load. All the tests were conducted according to a special test algorithm called a ''duration test''. This test algorithm was configured for a constant throttle position but variable engine speeds.

Bosch BEA-250 EU exhaust gas analyser that can be calibrated for LPG was used to measure the excess air ratio and concentrations of carbon monoxide (CO) (%) and hydrocarbon (HC) (ppm) emissions. The exhaust gas for the analysis was tapped from the exhaust pipe, approximately 1,20 m from the exhaust valve.

The noise suppression capabilities of designed filters were tested by using Gwinstek GDS 2204 digital oscilloscope which monitored all of the input and output signals of ECU also.

Table 3. Physical and chemical properties of propane, butane and gasoline.

Property	Propane	Butane	Gasoline
Liquid density, kg/m^3	509	585	765
Calorific value, MJ/kg	46,34	45,56	44,04
Boiling point, ^{0}C	-42	-0,5	30-210
Auto ignition temperature, ^{0}C	510	490	257
Flame temperature, ^{0}C	1980	1775	1720
Flame speed, m/s	0,4	0,4	0,35
Stoichiometric air/fuel, kg/kg	15,8	15,6	14,7
Lower flammability limit, vol.%	2,1	1,5	1,3
Upper flammability limit, vol.%	9,5	8,5	7,6
Octane number	111	103	95

5. RESULTS AND DISCUSSIONS

The highest frequency of inductive sensor output signal was calculated as approximately 5 kHz at 7500 rpm engine speed by using the elapsed time between the detection of 2nd and 1st pins and the signal whose frequency was higher than 5 kHz, was accepted as noise and the cut-off frequency of designed low-pass filter was selected as 5 kHz. The noise suppression capabilities of designed filters are shown in Figure 4 (a-b). Engine speed was approximately 300 rpm in Figure 4 (a). and it was detected that the signal to noise ratio increased by increasing the engine speed since the inductive sensor output signal level increased as shown in Figure 4 (b). The control signal of injectors is shown on the 3rd channel of oscilloscope in Figure 4 (b) too. Fuel injectors which were activated on the rising edge of control signal, were deactivated on the falling edge.
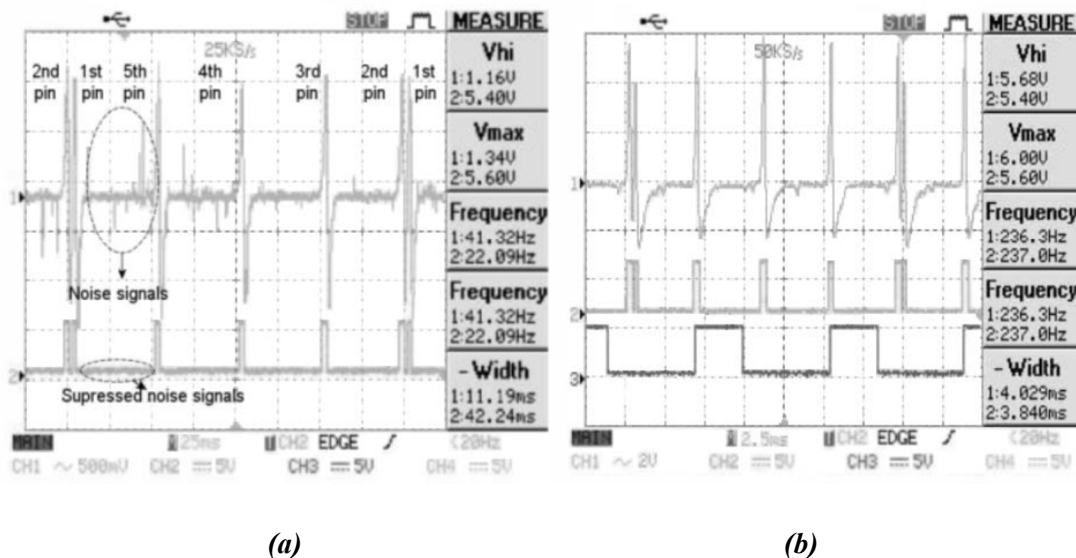

(a)   *(b)*

Figure 4:
Noise suppression capabilities of designed filters.
(a) *at approximately 300 rpm **(b)** at approximately 3750 rpm*

(a)

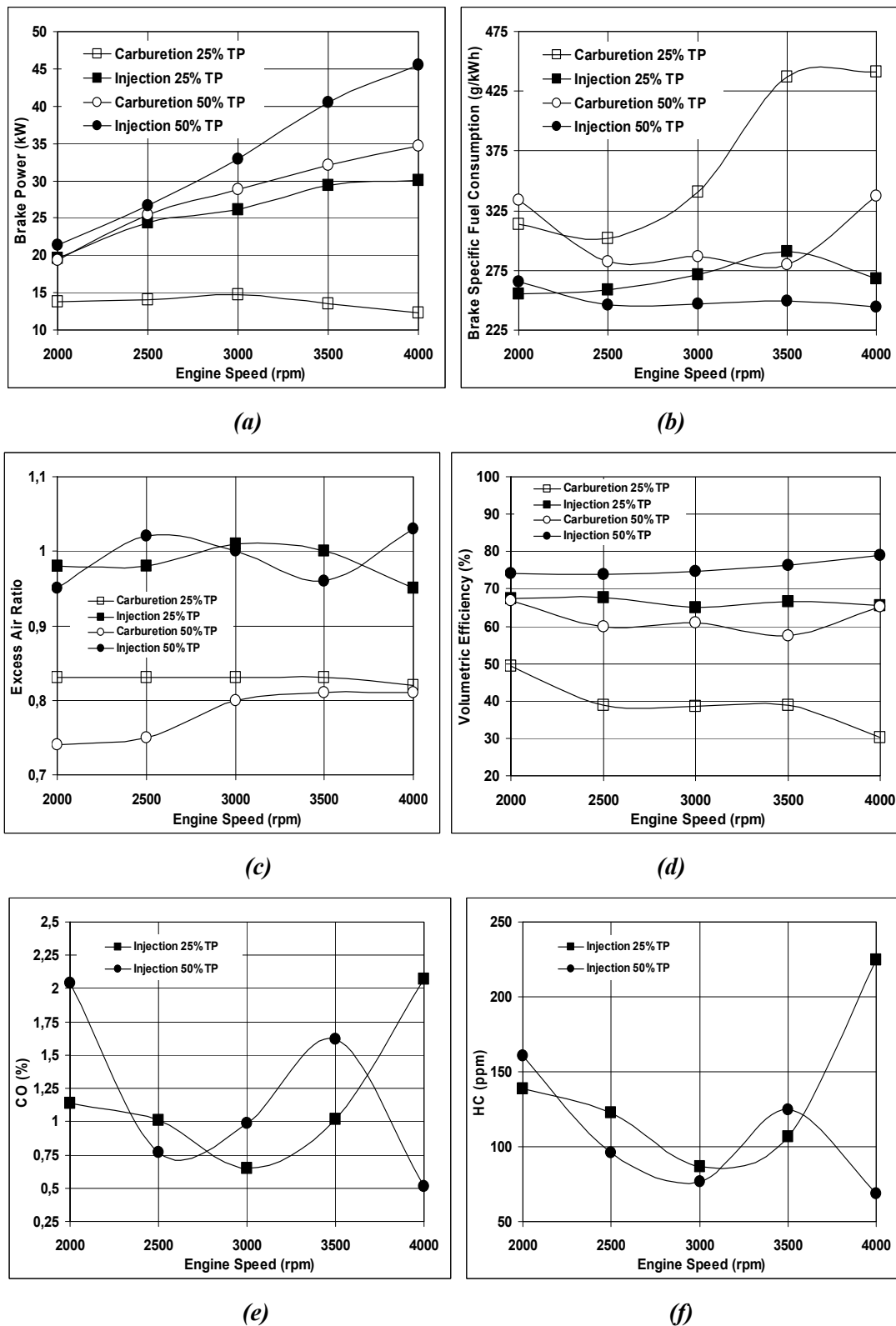
(b)

(c)

(d)

(e)

(f)

Figure 5:
Performance test results.
(a) brake power (kW) (b) brake specific fuel consumption (g/kWh)
(c) excess air ratio (d) volumetric efficiency (%) (e) CO(%) (f) HC (ppm)

The performance comparison results between carburetion and injection fuel supply methods are given in Figure 5 (a-b) and according to these figures; up to 145,26% and 31,44% improvements in brake power and up to 39,28% and 27,58% improvements in brake specific fuel consumption were obtained with injection compared to the carburetion at 25% TP and 50%TP respectively. The excess air ratio values realized during the tests with carburetion and injection are given in Figure 5 (c). According to the Figure 5 (c), test engine could be run at average excess air ratios of 0.98 and 0.99 with the injection system and 0,83 and 0,78 with the carburetion at 25% and 50% TP respectively, throughout the speed range. The improvement obtained in brake power at each test point is a result of better volumetric efficiency with injection system compared to carburetion (Figure 5 (d)). Brake specific fuel consumption at each test point is better also as a result of improvement in brake power and leaner mixture with injection system compared to carburetion. The CO and HC emission levels were obtained as averages of 1,18% and 136 ppm at 25%TP and 1,19% and 106 ppm at 50%TP, respectively throughout the speed range with LPG injection system as a result of working with closer excess air ratios to 1,0 (Figure 5 (e-f)).

6. CONCLUSION

- Gas-phase LPG injection electronic control unit was successfully designed for research projects in this study. Thanks to the injection control system designed as a base platform, upgrading of ECU can be performed easily by making simple modifications in hardware and software if desired.
- The noise signals caused by electromagnetic interference, could be suppressed by taking some measures such as using low pass filters, reducing the ground impedances, separating the grounds, breaking the ground loops, shielding the circuits and the cables, reducing both the length-width of transmission lines and the gaps between the ground patterns and the signal patterns.
- Improvements in engine performance compared to carburetion and acceptable exhaust emissions were obtained with designed LPG injection ECU.

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