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Improvement of the Electronic Control Unit for Ignition and Injection in a Wankel Engine

Bir Wankel Motorda Ateşleme ve Püskürtme Üniteleri İçin Elektronik Kontrol Ünitesinin Geliştirilmesi

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Abstract
In this study, an electronic control unit was designed and developed for a single rotor Wankel engine. The code was written the Arduino IDE. An interface is designed in Visual Studio for computer control of a single rotor test engine. Thanks to the control unit, the injection advance, injection duration, engine speed, dwell time and ignition advance were controlled. In the hardware part, firstly solid state relay was used for switching, and then a MOSFET circuit was tested. It was observed that the ignition and spraying signals received from the oscilloscope for both switching came regularly and continuously at different speeds (600, 1000 and 3000 rpm). Afterwards, according to the results obtained with the oscilloscope and high speed camera, there was no delay in opening time of the injector with the solid state relay. However, there was 0.6 milliseconds delay in closing time of it. This situation caused the engine to run erratically and unstable at high speeds. In the circuit established with Mosfet, there was no delay at the opening and closing times of the injector. As a result, it was concluded that it would be more appropriate to use the circuit designed with MOSFET in the control unit.

Keywords: Arduino Microcontroller, Electronic Control Unit, Ignition, Injection, Mosfet, Solid State Relay, Wankel Engine

Öz
Bu çalışmada, tek rotorlu bir Wankel motoru için elektronik kontrol ünitesi tasarlanmış ve geliştirilmiştir. Kod Arduino veri tabanında yazılmıştır. Tek rotorlu test motorunun bilgisayar kontrolü ile Visual Studio'da bir ara yüz tasarlanmıştır. Kontrol ünitesi sayesinde püskürtme avansı, püskürtme süresi, motor hızı, bobinin dolma süresi ve ateşleme avansı kontrol edilmiştir. Donanım bölümünde, ilk önce anahtarlama için katı hal rölesi kullanılmış ve daha sonra bir mosfet devresi ile test edilmiştir. Her iki anahtarlamada osiloskoptan alınan ateşleme ve püskürtme sinyallerinin düzenli ve sürekli olarak farklı hızlarda (600, 1000 ve 3000 rpm) geldiği gözlenmiştir. Daha sonra, osiloskop ve yüksek hızlı kamera ile elde edilen sonuçlara göre, katı hal rölesi ile enjektörün açılmasında herhangi bir gecikme olmamıştır. Ancak, enjektörün kapanması 0.6 milisaniye geciktiği gözlemlenmiştir. Bu durum, motorun özellikle yüksek hızlarda düzensiz ve dengesiz çalışmasına neden olmuştur. Mosfet ile kurulan devrede, enjektörün açılıp kapanmasında herhangi bir gecikme olmamıştır. Sonuç olarak, kontrol ünitesinde mosfet ile tasarlanan devrenin kullanılmasının daha uygun olacağı sonucuna varılmıştır.

***Anahtar kelimeler**: Arduino Mikro Denetleyici, Elektronik Kontrol Ünitesi, Ateşleme, Püskürtme, Mosfet, Katı Hal Rölesi, Wankel Motor*

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1. Introduction

Wankel engines are called rotary piston engines that operate according to the principle of four-stroke operation. The operating principle is different from piston engines. The Wankel engine has a rotor and eccentric shaft as a moving part (Cihan, 2017). Compared to the piston engine, there is no valve arrangement for the intake and exhaust process, and the charge change is provided through the ports on the side housings. The opening and closing times of the ports limit the side of the moving rotor (Wankel, 1963). The rotor assumes the role of the piston-connecting rod mechanism in reciprocating engines (Bensinger, 1973). To put a finer point on it, the rotor transmits power directly transmission to the output shaft by providing rotational motion due to the pressure generated by the burning gases (Ansdale, 1968). In this way, Wankel engines can reach high rotational speeds (Yamamoto, 1971). Furthermore, if evaluated in terms of parts of the engine, it is simpler and consists of fewer parts because there is no crank-connecting rod mechanism compared to the reciprocating engine (Yamamoto, 1981; Froede, 1961). The eccentric shaft rotates three rounds in one round of rotor in a rotary piston engine. There are three cycles in one round of the rotor, and one work is achieved in each round of the eccentric shaft (Keller, 1968). Other advantages of the Wankel engine can be listed such as lighter, lower NOx emissions, the ability to generate more power than a reciprocating engine with the same weight ratio, and vibration-free operation due to the absence of reciprocating masses such as piston and connecting rod (Bentele, 1961; Warner, 2009; Ohkubo et al., 2004; Yamamoto et al., 1972). Wankel engines find application in the aviation industry thanks to their advantages. Especially, the fact that the weight is less and the power density is higher increases the use of these engines in unmanned aerial vehicles. To date, many manufacturers have worked on the Wankel engine in the automotive industry (Kutlar et al., 2018). Today, only Mazda is carrying out serious work on the engine. With the improvements to be achieved thanks to the work on Wankel engines, it is envisaged that these engines will become much better in the future (Cihan et al., 2020).

Many studies have been conducted in the literature on the control of ignition and injection units in conventional piston engines. Kutlar in his study provided the control of ignition and injection in a single-cylinder four-stroke gasoline engine by adapting the necessary software and hardware onto the research engine over the computer. According to the sensitivity of the incremental encoder used in the study, advance and duration values were adjusted as desired, and the position of the throttle was changed and engine optimization was provided (Kutlar, 1999). Tekeli in his study, a control system was produced to control the variables such as cycle mode, injection time and ignition coil charging duration (dwell duration) of single cylinder gasoline engine. The engine has been controlled with the Arduino board. In injection and ignition experiments, it was observed that the control unit was working successfully (Tekeli, 2013; Tekeli et al., 2013). Again, the injection duration, injection time, ignition advance and dwell time of a four-stroke motorcycle engine were controlled as base engine speed and load values according to the engine map (Scafati et al., 2007). A four-stroke, two-cylinder motorcycle engine is controlled by a microprocessor-based unit. Thanks to the interface program communicated in series, it is possible to change parameters such as gas throttle position, intake air temperature, injection advance and dwell time according to the angle of the engine crankshaft (Tan and Hung, 2005). Aydın in his study, developed an Electronically Controlled Fuel System (ECFS) for a diesel engine. In this way, the instantaneous change of injection pressure, injection advance and injection duration is provided. Altera DE2 FPGA development kit was used for electronic control unit (ECU). The engine's instantaneous piston position and velocity measurement were provided by optical encoder (Aydın, 2018). In another study, an electronic control unit (ECU) was made for the gasoline engine. Arduino microcontroller was used. Code programming was done at the base C. The injection flow rate was measured by the ECU. Mass flow rate is calibrated by controlling pulse width (Jeeva et al., 2014). Ignition control system are designed for the ignition engine with an unique spark plug. The system is controlled by a microcontroller. The system has a computer attached to the microcontroller card. Engine speed and load are constantly controlled by the system. Depending on load and speed, the most appropriate ignition advance is calculated with the help of an advance map in computer software and the results are sent to the microcontroller. Thanks to the system, the most suitable ignition advance can be given (Batmaz et al., 2011). High accuracy results are obtained by creating optimum ignition and injection conditions with electronic control unit for a single rotor Wankel engine (Cihan, 2017; Özmen, 2015; Cihan et al., 2017).

The test engine used in this study is RENESIS RX-8 13B model Wankel engine of Mazda company. The reasons we prefer this engine are; the convenience of the supply of parts is that the engine dimensions are a new generation mass-produced engine suitable for the use of the measuring instruments required for the experiment. Ohkubo et al. gave extensive information about the engine (Ohkubo et al., 2004). The engine brake in the laboratory has a power of 70 kW. The RX8 engine gives approximately 170 kW of power, thus is insufficient to brake the existing engine. Therefore, the twin rotor motor chosen as the experimental engine was converted into a single rotor. Many parts have been modified during the conversion process. Some parts have been remanufactured in accordance with the single rotor prototype engine. According to single rotor system are adapted parts such as eccentric shafts, intake and exhaust manifolds, lubrication and cooling systems (Cihan, 2017).

Finally, a special electronic control unit has been prepared for the ignition and injection systems of the transformed engine. The control unit was designed in two different types. The Arduino Mega and Uno microcontroller cards were first used, followed by a solid state relay that allows switching. Ignition and injection of the engine is controlled with the code written in Arduino. Thanks to the code written, ignition advance, injection advance, injection duration, dwell duration and engine speed were controlled. An interface was designed in Visual Studio for computer control of a single rotor test engine. In the second type, a circuit was designed with a MOSFET (Metal Oxide Semiconductor Field Effect Transistor) instead of solid state relay. Then, a mosfet circuit was used for switching. In both cases, similar results were obtained from ignition and injection signals regularly occurred in different engine speeds. Thanks to the mosfet circuit, there was no delay in the values given from the computer for ignition and injection. Thus, the delay caused by the relay has been eliminated.

2. Material and Method

2.1 Hardware Section

A control unit was built in accordance with the ignition and injection elements of the single rotor test engine. At first, it was determined which software program will be used for ignition and injection in the control unit and accordingly the which microcontroller board will be used.

The Arduino Mega with Atmega 2560 microcontroller and Uno with Atmega 328 microcontroller were used for the control equipment. Both boards have the same function. But, the more comprehensive Atmega 2560 microcontroller was used. (Figure 1). Arduino is basically an easy-to-use electronic programming platform with an open source and flexible hardware/software architecture. Many drive circuits are in harmony with them. It has 54 digital input-output pins (14 of which can be used as PWM output), 16 analogue inputs, 4 hardware Serial ports (UART) and 16 MHz crystal oscillators and can be fed via USB port or with an external DC adapter (Taşdemir, 2013). The first focus on the hardware part is focused on the engine control unit works.

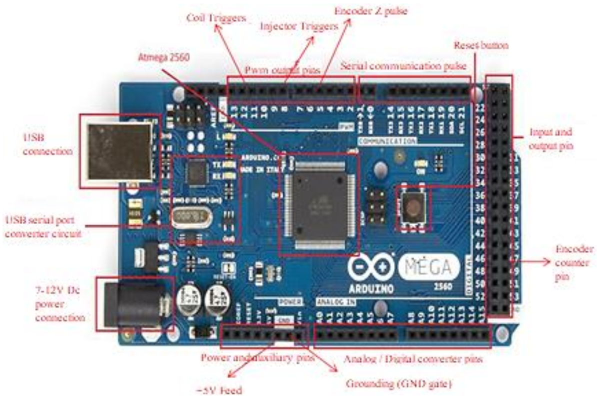


Figure 1. Arduino Mega 2560 board.

The amount of current coming out of the microcontroller is inadequate for the switching system used in our cases. Transistors are the first thing to come to mind when it comes to switching in electronics in general. Higher currents and voltages can be controlled with the low voltage and current coming out of the microcontroller through the transistor.

Transistors are available in different types on the market. In below are the most prominent varieties:

- BJT (Bipolar Junction Transistor): It is the simplest variety of transistor. It is suitable for high speed, average current and voltage controls.
- Mosfet: this kind of transistor is suitable for high speed, high current and voltage controls.
- Thyristor (Triac, Solid State Relay): It consists of a combination of multiple transistors. It has

average speed, and unlike the other two species, it can switch the alternative current.

Transistor types are divided into two as NPN and PNP. As seen in Figure 2, NPN transistor is used to turn the negative side on and off (Low side switching) and PNP transistors are used to turn the positive side on and off (High side switching).

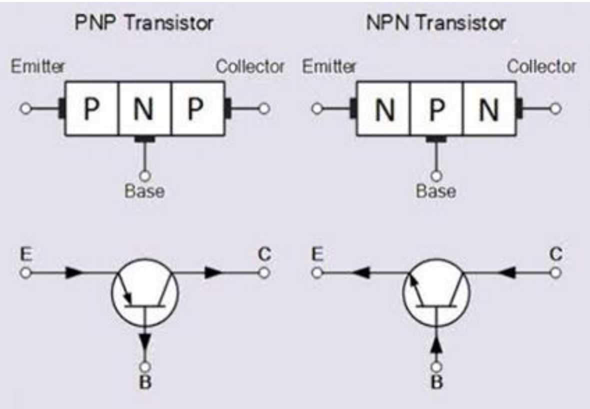


Figure 2. Schematic view of the transistor.

One of the transistors used for the single-rotor Wankel engine electronic control unit is the Solid State Relay (SSR). The SSR is a switching unit composed entirely of electronic components with control and power circuits that do the same thing as conventional relay and contactor (Cihan, 2017).

The technical specifications of the used relay;
Maximum allowable current for SSR: 10 A
Voltage and current range for input leads: 3-32 V / 4-20 mA
Voltage range for output leads: 5 to 60 V
Current direction at input output: DC-DC

Since the single rotor engine has 4 injectors and 2 ignition coils, it will be necessary to switch each individually. For this reason, a total of 6 SSR were used. There is a cooler used in the relays. Outside of this cooler, an aluminum rail is placed under the relays that will serve as additional cooling (Figure 3).

Figure 3. Used relay and cooler in system.

BJT can be used as a switch in non-high current circuits, but due to the high internal resistance of BJTs, it soon starts to warm up. Also, there may also be a voltage drop at the BJT output. The average current of 1.5 amp drawn by injector is a high amount for many transistors. Mosfet performs better for high currents due to its lower internal resistance. Mosfets are divided into two as N channel and P channel. N channels are used to turn on and off the negative voltage line (Low side switching) in the circuit and P channels are used to turn on and off the positive voltage line (High side switching). The MOSFET types using in electronic circuits are shown in Figure 4.

BJT is a current-controlled switch; it keeps the switch open when the current is interrupted and keeps the switch closed when there is current. Mosfet is a voltage control switch; when the voltage is applied, it turns on the switch, but continues to keep the switch on when the current is interrupted. In order to open the switch, the applied voltage must be pulled down to zero (N-Channel) or vice versa (P-channel). To do this, pull up or pull down resistors are required according to the mosfet type (Figure 5).

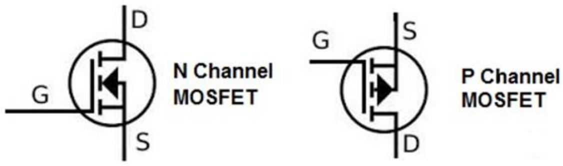


Figure 4. Schematic view of mosfet.

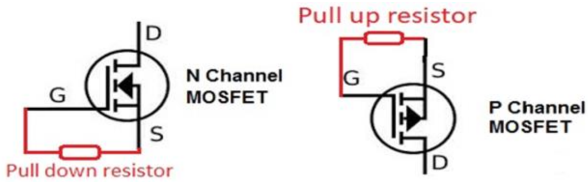


Figure 5. Schematic view of the BJT transistor.

In one side of the mosfet, there is a highly sensitive controller circuit, in the other side there is injector or ignition coil working at high current and voltages. It could be useful to isolate these two circuits electrically. Optocouplers are used for this purpose in electronics and optically separates the two circuits from each other. There is a led and a light sensor inside an optocoupler. When electricity is applied to the led side, the LED lights up and the light sensor turns on and when the current of the LED is interrupted, it turns off and turns the light sensor off (Figure 6).

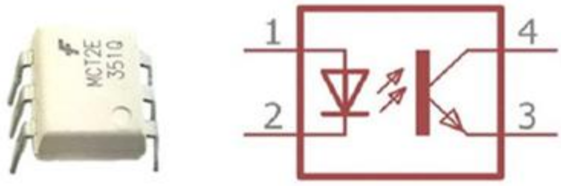


Figure 6. Optocoupler.

2.2 Software

Tekeli's study is based on the software of the control unit for the 3 LD 450 lombardine single-cylinder engine (Tekeli, 2013). A base (Özmen, 2015) is established in the control unit software of the single rotor Wankel test engine.

An interface is designed in Visual Studio for computer control of a single rotor test engine (Figure 7). There are separate injection durations and injection angles in terms of EA for the 4 injectors, separate ignition advances and dwell durations for the two spark plugs at the interface. Also, the engine speed is checked in order to calculate the dwell duration given in terms of angle.

When the engine is working, two ignition (leading and trailing spark plugs), four injections and one Z signal from the Arduino output were sent to the Kistler Kibox data collection device. In the Kister Kibox interface, ignition and injection analog signals are instantly displayed on V - CA diagram (Figure 8).

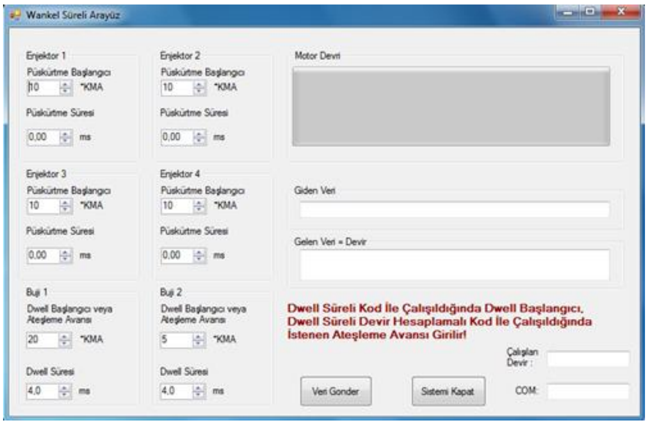


Figure 7. Interface developed for the control unit

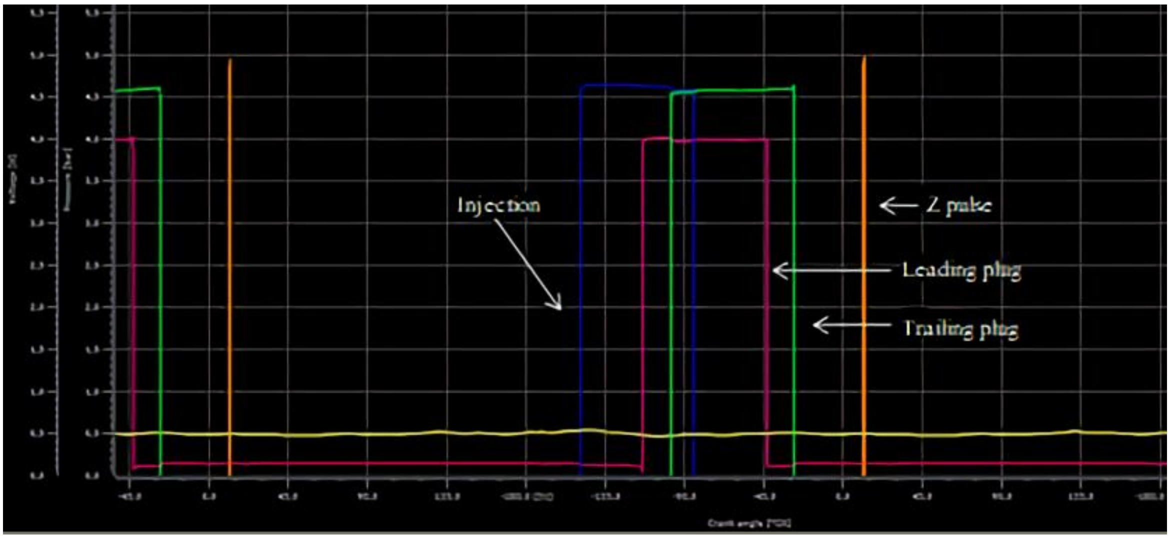


Figure 8. Ignition, injection and Z-signal was taken from Kistler in-cylinder pressure measuring device.

2.3 Establishment of Ignition and Fuel Injection Test Setup

The equipment used for ignition tests are ignition coils, spark plugs and high voltage cord. The ignition coil has three pins A, B and C (Figure 9). In previous ignition coil systems a separate ignition module had been used. The engine's original ignition coils includes the ignition module (Figure 9).

The recommended dwell duration (the charge duration of the ignition coil) for UF501 ignition coils is 4 milliseconds (URL-1, 2019). The amount of current passing through the coil were examined at different charging durations. In the experiments, it has been seen that dwell durations above 4 ms causes the coil to be overheated and malfunctioned. Experiments were conducted based on the recommended time (4 ms).

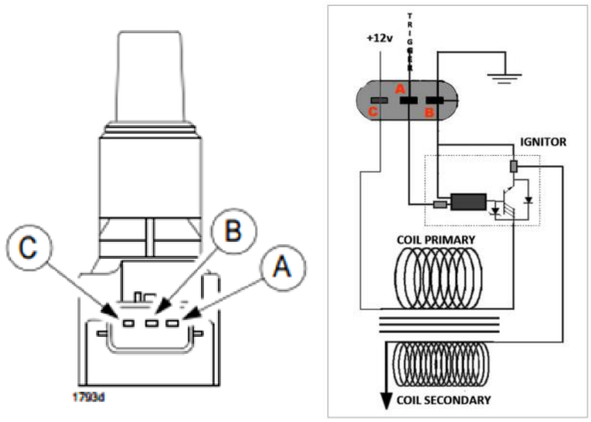


Figure 9. 13B MSP engine ignition coil pins and circuit diagram (RX8, 2003; URL-2, 2019).

The necessary software and hardware equipments for the ignition and injection experiment has been established (Figure 4). In the ignition system, the charging duration of the coil and the EA angle (ignition advance) at which the spark plug flashes are controlled. In the injection section, the start of injection and the injection duration in terms of EA could be controlled.

Heidanhain brand ROD426 model, 7200 pulse counting incremental encoder was used. With one full revolution of the encoder shaft, a cycle occurs in the engine. Moreover ignition and injection was performed within the given time interval. The explanation for the Encoder-Arduino board connection was given in Table 1. The here Z signal sends a signal to the Arduino every time the engine turns.

Table 1. Encoder connection

Pin number	Function
1	+5 V feed
4	Counter pin
5	Encoder Z pulse
7	(-)

In the experimental setup, the encoder was rotated by a drill and the number of rotations determined by mounting the engine encoder and it was seen that both of the plugs flashed one after the other. First the leading spark plug and then the trailing spark plug was flashed. Both spark plugs were flashed in different engine speeds. On the other hand, it has been determined that the injector sprays properly in the specified range and different engine speeds in each full round of the encoder (Figure 10).

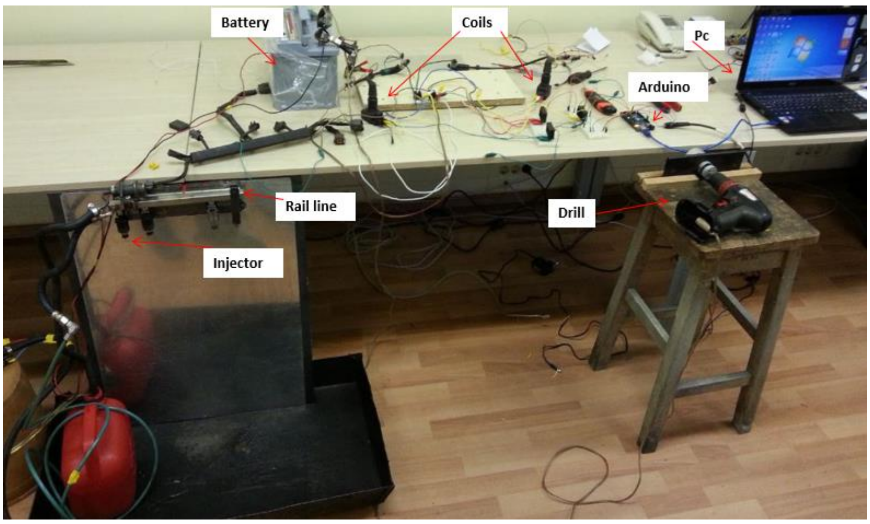
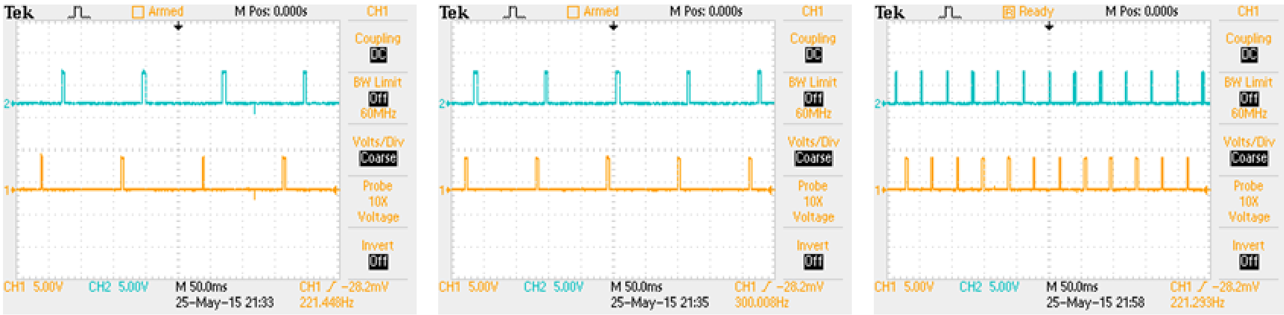


Figure 10. General testing apparatus for injection and ignition.

3. Results

In this study, an electronic control unit was developed for a single rotor Wankel engine. Arduino IDE is used to write code in the software section. An interface is designed in Visual Studio for computer control of a single rotor test engine. The injection advance, injection duration, engine speed, dwell time (Ignition coil charging time) and ignition advance were controlled with the

code written. Injector injection durations are around milliseconds in internal combustion engines today. As is known, it can be used in all three types of transistors for the engine control unit.
Experimental setups consisting of electronic control units installed with MOSFET and SSR were separately tested. During both experiments, similar results were observed that ignition and injection signals regularly occurred in engine speeds 600, 1000 and 3000 rpm with the drill. The test conditions are selected randomly among the possible working conditions of the engine. The delay times obtained from these test conditions was a constant value. The test results obtained from the oscilloscope are given in Figure 11. It has been seen in the results that the ignition and injection are stable without interrupting the signal.



a) 600 rpm **b)** 1000 rpm **c)** 3000 rpm

Figure 11. Ignition and injection signals at different engine speeds.

In Figure 12 the behavior of the Solid State Relay taken from an oscilloscope has been shown. In the figure, the blue line is the signal from the microcontroller and the yellow line is the output current of the relay. As could be seen, the relay has cut the current with a slight delay after the controller has interrupt the voltage.

Solid state relay's turn on time was the same as the signal coming out from the controller and does not have any delay. But there was a delay in turn off time happening after the signal of the microcontroller.

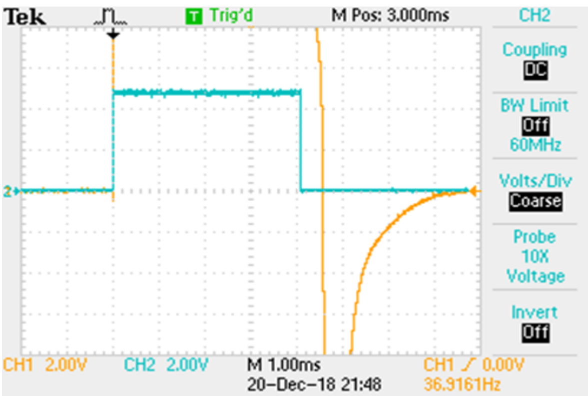


Figure 12. Delay of solid state relay.

As shown in Figure 12, this delay is 0.6 milliseconds. Even if this time is very small but it is equivalent to 7.2 EA at 2000 rpm and 10.8 EA at 3000 rpm in Wankel engine. As engine speed increases, the delay duration increased with Solid State Relay. This situation caused a serious loss and error in the engine. Also, it causes the engine to operate erratically. When MOSFET was used in the electronic control unit, the result from the oscilloscope was shown in Figure 13. As shown in Figure 13, there was no delay for the ignition and injection of the engine during the opening and closing time in the circuit made with MOSFET.

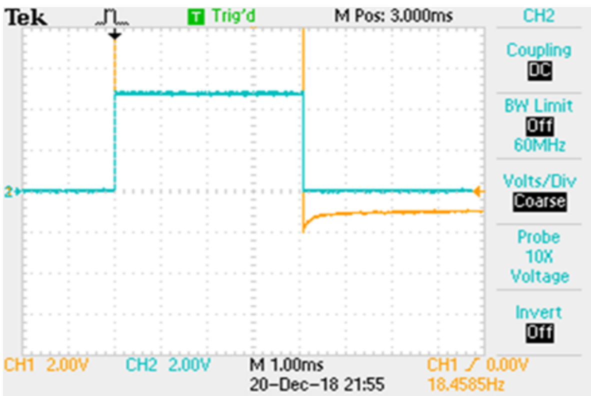


Figure 13. Delay in the mosfet circuit.

To see this issue more clear, an injector was tested with MOSFET and solid state relay outside the engine. Therefore, Photron brand Fastcam 512 high speed camera was used to determine the delay duration. The results were given in Figure 14 and Figure 15. Here, the opening and closing durations of the mosfet and solid state relay were compared. As seen, there was no difference between SSR and MOSFET at the opening duration of the injector (Figure 14). The closing duration is shown in Figure 15. As it is understood from the figures, the solid state relay closes the injector in 4.2 milliseconds, while mosfet has closed it in 3.6 milliseconds. This situation proved the 0.6 millisecond difference measured previously in the oscilloscope. For this reason, it is not suitable to use solid state relay for the switching task. Using MOSFET for switching in the engine control unit gave the most correct result in terms of proper and healthy operation of the engine.

Figure 14. Injector opening duration for SSR and mosfet.

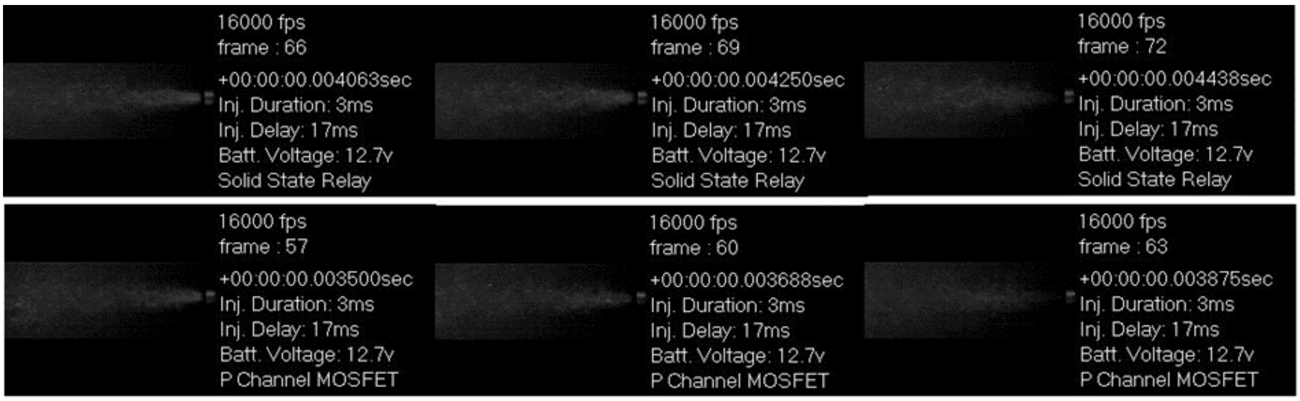
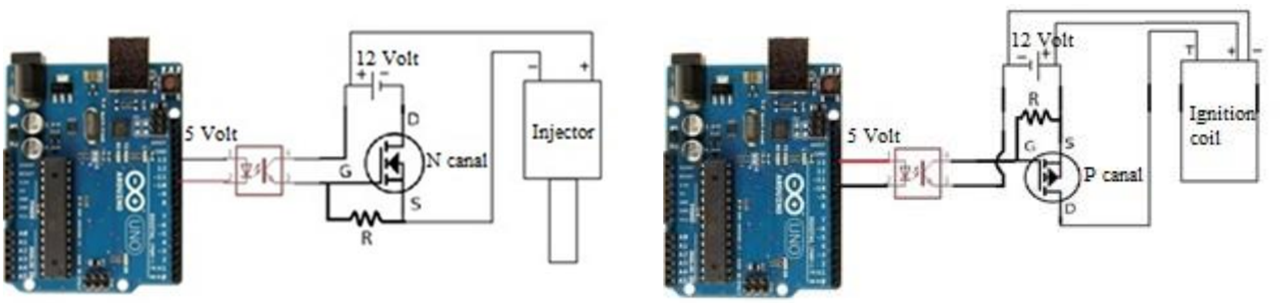


Figure 15. Injector closing duration for SSR and mosfet.

As a result, it was revealed that the circuit established with mosfet gives more accurate and realistic results. The figures below shows microcontroller board, optocoupler and circuit of the transistor to the ignition coil (Figure 16a) and the injector (Figure 16b).



a) Circuit installed for the injector

b) Circuit installed for the ignition coil

Figure 16. Electronic control unit circuits installed with mosfet.

4. Conclusions

In this study, electronic control unit (ECU) was designed and developed for a single rotor Wankel engine. Thanks to the ECU, the ignition, injection and engine speed of the engine have been controlled. The code for the software part of the control unit is written in the Arduino IDE. An interface was designed in Visual Studio for computer control of a single rotor test engine. Thanks to the code written, ignition advance, injection advance, injection duration, dwell duration and engine speed were controlled. SSR was used primarily for switching in the hardware part of the control unit. Afterwards, a mosfet circuit was used for switching.

The only disadvantage of using the MOSFET's in circuits is that they need pull up (for P-channel) or pull down (for N-channel) resistors in gate. The value of this resistor depends on species of the MOSFET and switching frequency. An optimum value for this resistor should be chosen otherwise the circuit will not work properly.

In both cases, similar results were obtained from ignition and injection signals regularly occurred in engine speeds 600, 1000 and 3000 rpm. Then, According to the results obtained with both oscilloscope and high speed camera, SSR's turn on time was the same as the signal from the controller and had not experienced any delays. But there was a delay in turn off time happening after the signal of the microcontroller. This delay was 0.6 milliseconds. When mosfet was used in the electronic control unit, there was no delay for the ignition and injection of the engine during the opening and closing time in the circuit made with mosfet. As a result, there was no delay by using MOSFET in the hardware part of the electronic control unit.

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