Analysis and Modeling of Ignition Timing Control for Gasoline Engines Using ECU

Pham Van Tuan, Nguyen Truong Huy

Abstract— **The paper presents a study on the analysis and development of an ignition timing control model for gasoline engines using an ECU to improve the combustion control efficiency in modern engines. The research focuses on analyzing the theoretical basis of the ESA electronic ignition system and the influence of ignition advance angle on engine power, fuel consumption and knocking phenomena. Based on this foundation, the control model was developed using an ATmega16 microcontroller integrated with simulated signals from the crankshaft position sensor, engine load sensor and engine speed sensor. The ignition control algorithm was programmed using CodeVisionAVR software and simulated in the Proteus environment to evaluate the system response under different operating conditions. Simulation results show that the control system ensures the correct ignition sequence, adjusts the ignition timing according to variations in engine speed and load and minimizes incorrect ignition timing phenomena. The study is significant for education and research in electronic engine control systems, as well as for the development of ECU models applied in modern automotive engineering.**

Index Terms— **ECU, ignition advance angle, gasoline engine, electronic ignition control**

I. INTRODUCTION

In recent years, along with the rapid development of electrical–electronic technology and automatic control systems, engine control systems in modern automobiles have increasingly adopted electronic technologies to improve operating performance, reduce fuel consumption and satisfy increasingly stringent emission standards. In modern gasoline engines, the ECU (Electronic Control Unit) plays a central role in managing important systems such as EFI (Electronic Fuel Injection), ESA (Electronic Spark Advance), exhaust emission control and other systems that optimize the combustion process. Among these, the ignition timing control system is considered one of the systems that directly affects engine power characteristics, thermal efficiency and fuel economy [1].

Ignition timing determines the formation and development of combustion pressure inside the cylinder. If the ignition advance angle is appropriately controlled, the maximum combustion pressure in the combustion chamber will occur approximately 10–15° crank angle after top dead center, thereby enabling the engine to achieve optimal torque and efficiency [2]. Conversely, excessively advanced or excessively retarded ignition timing reduces engine power, increases fuel consumption and raises harmful emissions. Studies conducted by Heywood indicate that optimizing ignition timing can improve the thermal efficiency of gasoline engines by approximately 5–10%, depending on operating conditions [1]. In addition, electronic ignition systems contribute to reducing HC and CO emissions by improving combustion quality and minimizing incomplete combustion phenomena [3].

In conventional ignition systems using mechanical mechanisms, ignition timing is typically adjusted by a distributor combined with centrifugal and vacuum advance mechanisms. Although this method has a simple structure, it presents several limitations, including low accuracy, slow response to changes in engine operating conditions and difficulty in optimization under varying working conditions. Furthermore, mechanical wear during operation may alter ignition timing, thereby reducing engine performance [4]. To overcome these disadvantages, electronically controlled ignition systems using ECUs have been developed and widely applied in modern automobiles.

In ESA systems, the ECU determines the ignition advance angle based on various input signals such as engine speed, engine load, coolant temperature, intake air temperature and knock sensor signals. The ignition angle is calculated according to an ignition map combined with correction factors to ensure that the engine operates close to the MBT (Maximum Brake Torque timing) region without causing knocking [5]. ECU-based ignition control improves ignition timing accuracy, optimizes engine power and reduces fuel consumption under various engine operating conditions. In addition, the knock sensor enables the ECU to automatically adjust ignition timing to protect the engine when knock occurs, thereby improving engine reliability and durability [6].

Although numerous studies have been conducted on electronic ignition systems and ignition timing control strategies, most current studies mainly focus on the general operating principles of ESA systems or integrated research within overall engine management systems. In-depth studies on independent ignition control models for research, simulation and educational purposes remain relatively limited. Moreover, many existing research models do not fully represent the relationship between engine speed, engine load and ignition timing variation under actual operating conditions. This limitation creates difficulties in studying ECU control algorithms as well as in modern automotive engineering education and training.

Manuscript received May 22, 2026

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Based on the above issues, this paper focuses on the research and development of an ECU-based ignition timing control model for gasoline engines in order to simulate the operating principles of electronic ignition control systems used in modern automobiles. The research includes analyzing the theoretical basis of ignition advance angle control, investigating the effects of engine speed and engine load on ignition timing, developing a control model using an ignition map-based control strategy combined with sensor input signals and simulating the ignition control process under different engine operating conditions. On this basis, the paper evaluates the applicability of the proposed model for research, education and the development of modern electronic engine control systems.

II. THEORETICAL BASIS AND PRINCIPLES OF IGNITION CONTROL

2.1. Overview of Ignition Timing

In gasoline engines, the air–fuel mixture is ignited by an electric spark generated from the spark plug at the end of the compression stroke. Since the combustion process requires a certain amount of time for the flame front to propagate throughout the combustion chamber, the spark must be generated before the piston reaches top dead center (TDC) in order to ensure that the maximum combustion pressure occurs at the most favorable moment for the power generation process [7].

The crankshaft rotation angle from the moment the spark is generated until the piston reaches TDC is called the ignition advance angle, commonly denoted as BTDC (Before Top Dead Center). The value of the ignition advance angle depends on the engine operating conditions and generally increases with engine speed [8].

If ignition occurs too late, engine power decreases and fuel consumption increases, whereas excessively advanced ignition timing may cause engine knocking and negatively affect engine durability [9]. In modern control systems, the ECU determines the optimal ignition timing based on signals from engine load, engine speed, temperature sensors and knock sensors in order to improve engine performance and reduce exhaust emissions [10].

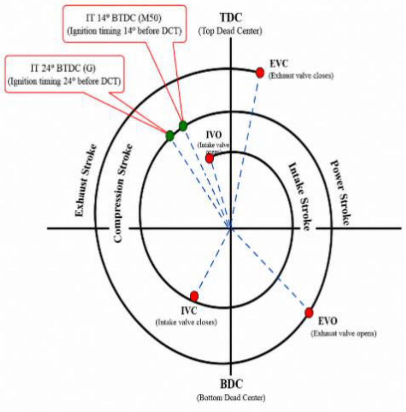

Figure 1. Illustration of Ignition Timing in a Gasoline Engine

2.2. Effects of Ignition Timing on Engine Performance

The ignition advance angle directly affects combustion pressure, engine power, fuel consumption and engine durability. If ignition occurs too early, the pressure inside the cylinder rises rapidly before the piston reaches top dead center (TDC), creating resistance against piston movement, reducing engine power and increasing the risk of knocking. This phenomenon also increases thermal load and vibration and may lead to damage to the piston, valves, or connecting rod bearings [11].

Conversely, when ignition occurs too late, the maximum pressure appears after TDC, reducing the mean effective pressure of the cycle and consequently decreasing engine torque and power. In addition, incomplete combustion increases fuel consumption and raises HC and CO emissions in the exhaust gas [12].

In modern engines, the ECU continuously controls ignition timing near the MBT (Maximum Brake Torque timing) region, which is the ignition timing corresponding to the maximum brake torque. Under this condition, the maximum combustion pressure typically occurs approximately 10–15° crank angle after TDC, thereby ensuring optimal power generation efficiency [7]. The actual ignition timing is determined according to the following relationship:

$$\theta = \theta_{base} + \theta_{corr}$$

In there :

- θ_{base}: basic ignition timing determined according to engine speed and engine load;
- θ_{corr}: correction angle corresponding to operating conditions such as temperature, knocking, supply voltage and acceleration mode.

Thanks to its continuous correction capability, the ECU enables the engine to operate close to the optimal region, thereby improving thermal efficiency, reducing fuel consumption and minimizing exhaust emissions [13].

2.3. Parameters Affecting Ignition Timing

Engine speed and engine load are the two most important parameters affecting the ignition advance angle. As engine speed increases, the time required for the piston to move toward TDC decreases, while the combustion duration of the air–fuel mixture remains nearly constant. Therefore, the ECU must increase the ignition advance angle to maintain the occurrence of maximum combustion pressure at the optimal position [8].

Engine load also directly affects the combustion rate of the air–fuel mixture. Under low-load conditions, the mixture burns more slowly and therefore requires earlier ignition timing. Conversely, at high loads, increased combustion chamber pressure and temperature accelerate the combustion process, so the ECU reduces the ignition advance angle in order to prevent knocking [10].

In addition, knocking is an important factor in ignition control. When the knock sensor detects abnormal engine vibrations, the ECU automatically retards the ignition timing to reduce the maximum cylinder pressure and protect the engine. After the knocking phenomenon disappears, the ECU gradually advances the ignition timing again to return the engine to the optimal MBT region [11]. The modern control principle is “advance the ignition timing as much as possible without causing knock.”

2.4. ECU Input Signals

To accurately determine ignition timing, the ECU utilizes signals from various sensors. Among them, the CKP (Crankshaft Position Sensor) provides information about engine speed and crankshaft angular position, serving as the primary signal for determining spark timing [10].

The CMP (Camshaft Position Sensor) enables the ECU to identify the operating stroke of each cylinder, which is especially important in COP (Coil-On-Plug) ignition systems. MAP or MAF sensors are used to determine engine load through intake manifold pressure or intake airflow rate, thereby allowing ignition timing adjustment according to actual operating conditions.

In addition, the TPS (Throttle Position Sensor) reflects the driver's load demand, while the ECT (Engine Coolant Temperature Sensor) supports ignition timing correction during cold starting and engine warm-up conditions. Particularly, the Knock Sensor is responsible for detecting knocking phenomena so that the ECU can automatically reduce the ignition advance angle, thereby protecting the engine and maintaining operational reliability.

III. METHOD FOR DEVELOPING THE CONTROL MODEL

3.1. Structure of the Control System

The electronic ignition control system consists of the ECU as the central control unit, which receives signals from various sensors and coordinates the operation of the power control module, ignition coil and spark plug in a closely integrated manner. Sensors such as the crankshaft position sensor, camshaft position sensor, intake air temperature sensor, engine coolant temperature sensor, throttle position sensor and knock sensor are responsible for collecting information regarding the engine operating conditions. The sensor signals are transmitted to the ECU for processing and calculation of the optimal ignition timing.

Subsequently, the ECU sends control signals to the power control module and the ignition coil. The ignition coil functions to convert the low voltage supplied by the battery into high voltage for the spark plug. The spark plug then generates an electric spark to ignite the air–fuel mixture inside the cylinder, enabling the engine to operate efficiently, stably and with reduced fuel consumption.

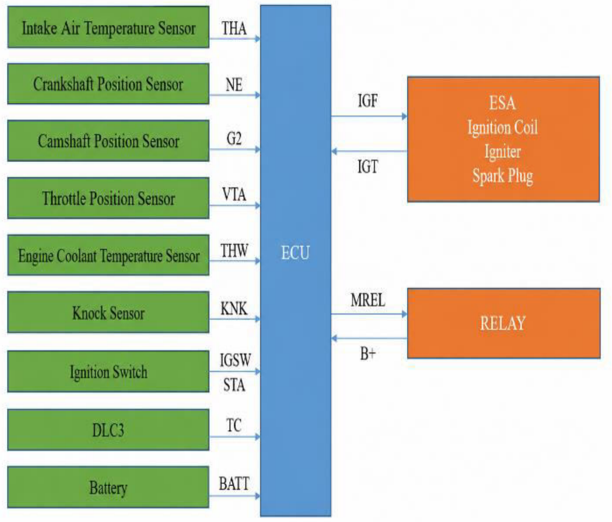

Figure 2. Block Diagram of the Ignition System

3.2. Ignition System Control Circuit

The electronic ignition system control circuit uses the ECM as the central processing and control unit for managing the ignition process of each cylinder through independent ignition coils. Engine speed signals are determined from the crankshaft position sensor and camshaft position sensor, which provide information regarding rotational speed and piston position. At the same time, engine load signals are obtained from the throttle position sensor and other related sensors to reflect the engine operating condition.

Based on these input signals, the ignition timing calculation module within the ECM determines the optimal ignition timing for each operating mode. Subsequently, the ECM sends the IGT control signal to the ignition coil control module to switch the primary current on and off, thereby generating high voltage in the secondary winding. This high voltage is then delivered to the spark plug to generate an electric spark for igniting the air–fuel mixture inside the cylinder.

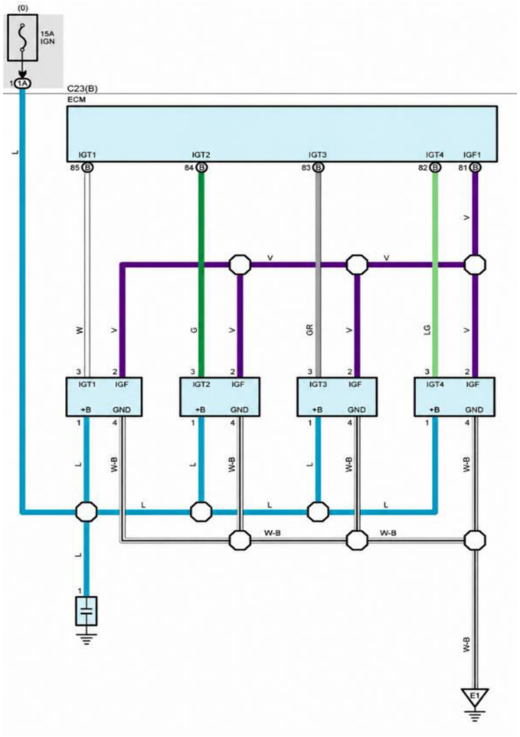

Figure 3. Ignition System Control Circuit

IV. RESULTS AND DISCUSSION

4.1. Using CodeVisionAVR Software for ECU Programming

CodeVisionAVR is an integrated development environment designed for AVR microcontrollers, supporting C programming language with a user-friendly interface and hardware configuration capability through the Wizard utility. The software integrates peripheral control libraries such as LCD, UART, ADC and Timer, thereby reducing the development time of embedded systems. In addition, CodeVisionAVR supports C compilation, AVR assembly language, simulation, debugging and communication with programming devices such as STK-500, contributing to improved program stability and reliability.

The ATmega16 microcontroller is an 8-bit microcontroller based on the RISC architecture, capable of executing instructions at high speed, reaching approximately 1 MIPS/MHz. The device integrates 16 KB Flash memory, 1 KB SRAM, 512 bytes EEPROM, 32 input/output pins and various peripherals such as Timer/Counter modules, a 10-bit ADC, USART and two-wire serial communication. Therefore, the ATmega16 is suitable for embedded control systems and electronic ignition system simulation applications.

The LCD display is used to present system operating information. The LCD consists of power pins, control pins and data pins. Specifically, the VEE pin is used for contrast adjustment, the RS pin selects either the data register or command register, the RW pin determines read/write mode and the E pin activates the display module. The DB0–DB7 pins are responsible for data transmission between the microcontroller and the LCD.

The engine control module consists of an encoder motor, an SW-SPST switch and a POT-HG potentiometer. The encoder motor simulates the engine crankshaft, while the potentiometer functions similarly to a throttle valve, allowing rotational speed variation by adjusting the voltage supplied to the motor. The SW-SPST switch performs the function of connecting or disconnecting the power supply to the system.

The transistor, transformer and LED module simulates the operating principle of the ignition system. Transistors Q1–Q4 operate as electronic switches, receiving control signals from the ATmega16 to switch the current through the primary winding of the transformer on and off. The transformer acts as the ignition coil, converting low voltage into high voltage. The yellow LED is used to simulate the spark plug; when the LED illuminates, it indicates the moment at which the spark plug generates an electric spark to ignite the fuel–air mixture inside the cylinder.

4.2. Simulation Results of the System

After completing the model and control algorithm, the program code was uploaded to the circuit, followed by system operation and testing.

Correct ignition timing operation.

The simulation results show that the electronic ignition system operates stably and ensures correct ignition timing according to the engine firing order. Control signals from the ATmega16 microcontroller are transmitted to the power transistors to switch the current flowing through the primary winding of the ignition coil on and off. When the primary current is interrupted, the ignition coil generates a high voltage in the secondary winding and delivers it to the spark plug to produce an electric spark. In the simulation, the ignition status is represented by the illumination of LEDs corresponding to each spark plug.

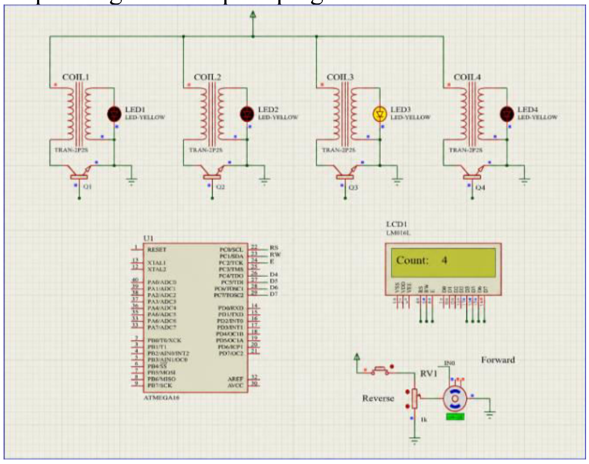

Figure 4. Simulation of Correct Ignition Timing

Correct ignition operation is identified when the spark plug generates a spark at the end of the compression stroke, thereby ensuring efficient combustion of the air–fuel mixture. The engine speed signal is simulated through the crankshaft encoder, while the RV1 potentiometer functions as a simulation of engine load or throttle opening. When engine speed changes, the microcontroller adjusts the transistor triggering timing accordingly to maintain the optimal ignition advance angle.

The simulation results indicate that the spark plugs operate sequentially without pulse overlapping or incorrect ignition timing phenomena. This demonstrates that the control circuit possesses good signal synchronization capability and satisfies the accuracy requirements of an electronic ignition system, thereby contributing to improved combustion efficiency and stable engine operation.

Advanced ignition timing.

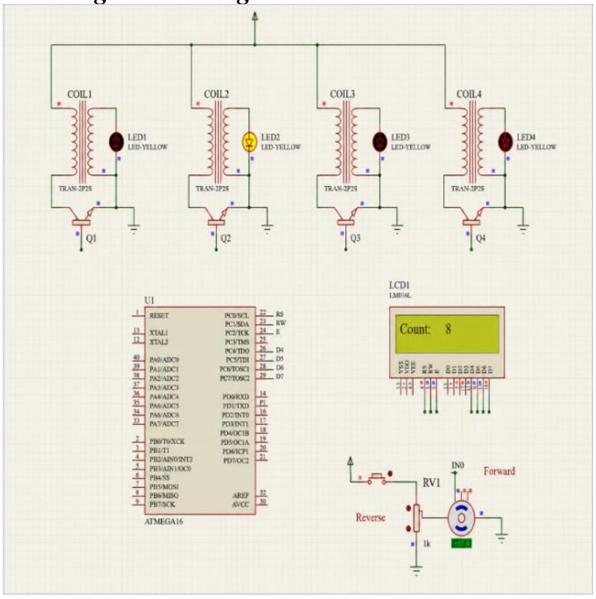

Figure 5. Simulation of Advanced Ignition Timing

The ignition system in the model uses the ATmega16 microcontroller to sequentially control four ignition coils while simulating engine speed signals through a potentiometer and a crankshaft position sensor. Based on this operating principle, the advanced ignition phenomenon can be analyzed as follows.

Advanced ignition is the process in which the spark plug generates an electric spark before the piston reaches top dead center (TDC) at the end of the compression stroke. Establishing an appropriate ignition advance angle allows sufficient time for the air–fuel mixture to burn, thereby enabling the maximum combustion pressure to occur shortly after TDC and improving the engine power output efficiency. In the model, the microcontroller is responsible for determining the triggering time of the power transistors to supply current to the ignition coils, thereby accurately controlling the spark discharge timing.

As engine speed increases, the actual combustion duration of the air–fuel mixture remains nearly constant; therefore, the ignition advance angle must increase correspondingly to ensure that combustion is completed at the proper moment. However, if the ignition advance angle becomes excessively large, it may cause knocking, increase thermal load and reduce engine durability. Conversely, excessively retarded ignition timing decreases engine power and increases fuel consumption. Therefore, electronic control of ignition advance timing is an important solution for optimizing performance, fuel economy and durability in modern engines.

V. CONCLUSIONS

The paper analyzed the theoretical basis of the electronic ignition control system used in modern gasoline engines and clarified the effects of ignition timing on engine power, thermal efficiency, fuel consumption and knocking phenomena. The analysis indicates that optimal ignition timing control plays an important role in improving engine performance.

The study successfully developed an ignition timing control model using the ATmega16 microcontroller combined with simulated signals of engine speed, engine load and crankshaft position. The model reflects the fundamental operating principles of the ESA system and satisfies the requirements for research and educational applications in electronic engine control.

Simulation results obtained from Proteus software demonstrate that the system operates stably, while the ignition coils and spark plugs function according to the correct firing order without pulse overlapping or signal deviation phenomena. The ignition timing is appropriately adjusted according to variations in engine speed and engine load, ensuring synchronization and accuracy of the control system.

The proposed research model has strong potential for application in teaching, research and development of modern electronic engine control systems. The research results provide a foundation for future developments such as constructing experimental ignition maps, integrating knock sensors and optimizing ECU control algorithms to improve engine performance and reduce exhaust emissions.

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