Research on Drive Control of Piezoelectric Injector

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Abstract. This article is based on PWM switching power supply technology, using high-performance SoC SCM ADμC841 as the main control unit and through the IGBT on-off control, the drive circuit of the piezoelectric injector is designed. The simulation model of the drive circuit is established by Matlab/Simulink. According to different current trends during charging and discharging, three current driving modes were simulated and analyzed. The test results show that the variable duty cycle based on current feedback uses an approximate trapezoidal current charging method, which not only has a faster charge-discharge speed, but also can effectively limit the maximum current, and has a stable charge and discharge process. Therefore, the variable duty ratio is the best driving method among the three driving methods.

Introduction

In order to meet the requirements of modern diesel engines to reduce energy consumption and improve emissions, high-pressure common rail fuel injection technology has been produced, and has become the main direction of current diesel engine technology development [1-8].

As a key component in the common rail system, the electronically controlled injector is decisive for the performance of the common rail system [9]. The piezoelectric injector with the piezoelectric crystal as the actuator replaces the electromagnetic force with the piezoelectric force, omitting the transmission process by the spring force [10], and improving the response speed. Moreover, the piezoelectric actuator can also control the lift and rise speed of the injector needle under the action of voltage [11], which provides greater technical support for the flexible control of the injection rule. In order to take advantage of the piezoelectric injector, it is necessary to adopt appropriate drive control circuits and control strategies.

At present, most of the drive control circuits for piezoelectric ceramic actuators are studied for static applications with precise positioning, and the application of piezoelectric actuators on injectors reflects the high-frequency dynamic characteristics of piezoelectric actuators. This is a new application area for piezoelectric actuators. The existing static drive circuit is prone to self-oscillation, has an influence on circuit stability, and has poor adaptability, and is not suitable for use in a piezoelectric injector. According to the design requirements of the driving circuit of piezoelectric injector, this paper designs a high-performance SoC microcontroller ADμC841 as the control core. And the driving circuit of the piezoelectric actuator is controlled by the power switch tube being turned on and off. The single peak, fixed duty cycle PWM, variable duty cycle PWM drive control strategy was simulated and analyzed, and the test platform was built to test the circuit with the best performance.

Piezoelectric Injector Drive Control Design

Drive control Design

The piezoelectric injector drive control mainly performs two functions: one is to provide a sufficiently high voltage to achieve a large displacement of the piezoelectric crystal output. The
second is to achieve fast charge and discharge, and obtain a fast response of the piezoelectric injector. According to the requirements of the piezoelectric injector drive control function, based on the PWM switching power supply technology, the microcontroller is used as the control core and the power switch device is used to complete the design of the piezoelectric injector drive circuit. The principle of the piezoelectric injector drive circuit is shown in Figure 1. The drive circuit design can be considered in two parts. First, based on the control circuit part of the microcontroller. Second, based on the control function implementation part of the power switch tube, that is, the charge and discharge power circuit portion.

![Figure 1. Block diagram of the piezoelectric injector drive circuit.](image)

**Drive Control Work Process**

The schematic diagram of the drive circuit is shown in Figure 2. The host computer can communicate with the single-chip microcomputer through the serial port circuit and send control instructions to the microcontroller. The rotational speed signal of the diesel engine is sent by a pulse signal generating mechanism, and the microcontroller receives the rev pulse signal through the external interrupt port and controls the injection start time and the injection frequency according to the signal. The load signal of the diesel engine is an analog quantity, which is sent by the load regulation signal circuit. The MCU receives the analog load signal through the analog-to-digital conversion port ADC0 and controls the time interval from the end of the charging signal to the start of the discharge signal according to the signal, that is, the length of the fuel injection duration. Thereby the control of the fuel injection amount is completed.

The PWM control signal sent by the single chip microcomputer is driven to control the power switch tubes G1 and G2 after the control signal is amplified by the isolation circuit. Among them, G1 is driven by the high side and is turned on during charging, G2 is driven by the low side and works when discharging. D1 and D2 are internal anti-parallel diodes of G1 and G2 respectively. The inductor L is connected in series in the charging and discharging circuits to protect the switching tube and the piezoelectric ceramic from the surge current, and adjust the current amplitude during charging and discharging through the PWM signal outputted by the control circuit. Resistor R measures loop charge and discharge current for feedback control and circuit protection. After the current signal passes through the sampling resistor R, it is converted into a voltage signal. After entering the signal processing circuit, it enters the analog-to-digital conversion port ADC1 of the MCU. After the MCU obtains the feedback signal, the output PWM control signal is adjusted according to the control strategy. The different configurations of the power switch tubes G1 and G2 being turned on or off under the action of the control system lead to the circuit generating different charging and discharging currents, which in turn leads to the piezoelectric actuator generating a corresponding telescopic effect and achieving a control target.
Research on Driving Strategy of Piezoelectric Drive Circuit

In practical applications, the basic driving modes of the piezoelectric actuator driving circuit can be divided into three types according to the different current trends during charging and discharging: single peak current driving mode, multi-peak current driving mode and trapezoidal current driving mode. As shown in Figure 3. Different driving methods are realized by different switch combinations of IGBT tubes under the control system. This paper is based on Matlab/Simulink simulation software, and mainly uses Simulink basic module library and SimPowerSystems module library two entity graphical simulation model library to build the simulation model of the driver circuit [12-13]. The model as a whole is shown in Figure 4. The model is used to simulate and analyze the three driving modes in turn, optimize and compare the control strategies, and analyze the influence of the specific parameters of the driving circuit on the performance. And the driving performance test of variable duty cycle driving mode is carried out on the development of driving circuit.

![Figure 2. Schematic diagram of the drive circuit.](image)

![Figure 3. The basic drive model schematic diagram of the piezoelectric actuator.](image)

Research and Analysis of Single Peak Drive Control Strategy

In the single peak current drive mode, the inductance has a great influence on the charge-discharge time and current. The equivalent capacitance of the piezoelectric actuator is 7μH. In the simulation model, the DC high voltage power supply is 180V and the loop resistance is 4.8Ω. The inductance...
values were set to 10μH, 48μH and 90μH respectively. Simulation obtains that the current waveform passing through the piezoelectric actuator during charging is shown in Figure 5. The voltage waveform of the piezoelectric actuator is shown in Figure 6.

As can be seen from Figure 5, increasing the inductance reduces the rate at which the current rises and falls, delays the time at which the current reaches the peak, and suppresses the magnitude of the current peak. As can be seen from Figure 6, as the inductance increases, the voltage rises slowly in the initial stage and rises rapidly in the later stage. When the inductance is too large, a voltage oscillation occurs. Taking into account control objectives, such as current peak limit, accelerate charging speed, ensure no current overcharge and voltage oscillation, take the inductance L = 48μH.

![Simulation model of the drive circuit.](image)

Figure 4. Simulation model of the drive circuit.

![Single peak charging different inductance value current simulation waveform.](image)

Figure 5. Single peak charging different inductance value current simulation waveform.

![Single peak charging voltage waveform with different inductance values.](image)

Figure 6. single peak charging voltage waveform with different inductance values.

It can be seen from the whole research process of the single-peak driving method that the single-peak current driving mode is simple, convenient to implement, and has a fast response speed. However, during the charging and discharging driving process, excessive peak current is easily generated, resulting in a decrease in system reliability.

**Research and Analysis of Fixed Duty Cycle PWM Control Strategy**

The fixed duty cycle PWM control strategy utilizes the freewheeling action of the inductor to temporarily turn off the signal during the climb phase before the current reaches its peak, the current still exists, and the amplitude gradually decreases. Turning on the signal again, the current will rise again under the voltage difference, thus achieving a multi-peak current drive mode.

In order to obtain the best performance indicators, it is necessary to study the influence of the PWM control signal on the drive circuit. In the simulation model, the equivalent capacitance of the piezoelectric actuator is 7μF, the DC high voltage power supply is set to 160V, the loop resistance
is 1Ω, the inductance is 10μH, and the frequency of the PWM signal is 100 kHz. The PWM duty cycle is set to 10%, 20%, and 30%, respectively, to analyze the effect of duty cycle on the drive process.

The simulated waveform from Figure 7 shows that as the duty cycle increases, as the charge/discharge time increases during each cycle, the corresponding charge/discharge voltage rises or falls at a higher rate. This helps to improve the performance of the response piezoelectric actuator. As can be seen from Figure 8 increasing the duty cycle will increase the drive peak current. It is reasonable to consider choosing a 20% duty cycle.

The fixed duty cycle PWM control signal realizes multi-peak current drive mode, which can effectively limit the maximum current peak and realize the software control of the drive circuit loop current. However, the fixed duty ratio also greatly suppresses the response speed of the piezoelectric actuator. As the equivalent capacitor charges and discharges, the voltage difference between the voltage across the capacitor and the target voltage gradually decreases. During the post-charge and discharge process, the circuit will not generate excessive peak current, so the duty cycle can be increased to increase the response speed.

![Figure 7. Pre-voltage waveforms of different duty cycles during charge and discharge.](image1)

![Figure 8. Pre-current waveform of different duty cycle charge and discharge.](image2)

### Research and Analysis of Variable Duty Cycle PWM Control Strategy

The implementation of the variable duty cycle PWM control signal can be based on current feedback control. The basic idea is to set a maximum limit on the current flowing through the equivalent capacitance of the piezo actuator. When the loop current measured by the current feedback circuit is higher than this set value, the charge/discharge signals are temporarily turned off during the PWM period to suppress the increase of the duty ratio. Then the charge/discharge signal is reopened in the next PWM cycle, and the duty cycle is continuously corrected. The limit value of this current can be obtained from the technical data of the IGBT. In this paper, the PWM frequency is set to 100 kHz, the current limit can be set to a maximum of 18A.

The variable duty cycle PWM drive control strategy based on current feedback has a complicated implementation of charge and discharge control signals. Figure 9 shows the specific block diagram of the charging signal in the simulation model. The implementation of the discharge signal is similar.
In the variable duty cycle PWM drive control, in addition to considering the inductance, the influence of the resistance value on the drive performance of the circuit must also be considered. The equivalent capacitance of the piezoelectric actuator is 7 μF. In the simulation model, the DC high voltage power supply was set to 160V, the inductance was set to 30μH, and the analog current limit was set to 18A.

Excessive inductance has excessive inertia and freewheeling capability, which will cause overcharging or over discharging of the capacitor, causing current and voltage fluctuations, thereby affecting the performance of the piezoelectric actuator. The oscillation of the circuit is closely related to the size of the resistor. Set the resistance to 2Ω, 3Ω and 4Ω respectively. The effects of different resistance values on the drive performance were investigated. It can be seen from the simulation results in Figure 10, Figure 11 and Figure 12 that increasing the resistance has little effect on the voltage rise and fall speed, it will suppress the current and voltage fluctuations in the circuit. This is because the drive circuit is basically the inertial link of the inductor and energy storage, and the resistor is the damping link of the system. Increasing the resistance can suppress oscillations, making the system more stable and convergent. At the same time, however, it should be considered that an increase in resistance increases the power consumption of the drive circuit. So choose a 3Ω resistor.

The simulation results show that the single-peak drive control is easy to implement, the control is simple, and the response speed is fast, but a large peak current is generated. A fixed duty cycle PWM drive control strategy enables multi-peak current charging. It can effectively control the maximum peak current, but it also greatly suppresses the response speed of the piezoelectric actuator. The variable duty cycle PWM drive control strategy based on current feedback implements an approximate trapezoidal current charging mode. It has a fast charging and discharging speed, and can effectively limit the current maximum. The charging and discharging process is also stable. The piezoelectric actuator drive circuit is undoubtedly the best choice in terms of driving effect. Therefore, the following paper only introduces the circuit test of the variable duty cycle PWM drive control strategy.
Variable Duty Cycle PWM Control Drive Circuit Test

Set up a drive circuit test platform, as shown in Figure 13. The charge/discharge voltages and currents across the piezoelectric ceramic were observed and recorded by a Tektronix oscilloscope, where the measurement of the charge/discharge current was indirectly reflected by the voltage measurement across the resistor R. The Tektronix oscilloscope model used in the experiment is TDS2024C, which can communicate with the PC through the USB interface, and realize the real-time recording of the test results through the PC desktop software.

The power wire wound resistor used in the test is 2.5 Ω. The inductance is 33μH. Set the high voltage DC power supply to 160V. The current limit is 15A. The frequency of the PWM signal is 100 kHz.

The current and voltage waveforms of a charge and discharge cycle on the drive circuit are shown in Figure 14. The separate charging and discharging processes are shown in Figure 15 and Figure 16 respectively. It can be seen from the voltage waveform of the charging and discharging process that under the control of the variable duty PWM signal, the voltage change is smooth and rapid, and the charging and discharging process only takes 0.12 ms.

The separately amplified charge and discharge current waveforms are shown in Figure 17 and Figure 18 respectively. It can be seen from the current waveforms of the charging and discharging process in Figure 17 and Figure 18 that the current peak is strictly limited under the control of the variable duty cycle PWM signal based on current feedback. If the current reaches a peak value, the charge and discharge signal will be temporarily turned off during this PWM signal period and will be re-opened until the next PWM period. During the PWM period in which the charge and discharge signals are temporarily turned off, the freewheeling action of the inductor allows the current to continue to exist and charge and discharge the equivalent capacitor. The current will be smaller and away from the peak. But because the PWM signal has a higher frequency, the next PWM signal will come quickly and the current will rise again. Therefore, the current of the entire charging and discharging process has a high average value, and the charging and discharging process can be completed relatively quickly.
Summary/Conclusion

1. Single peak current drive mode control is simple, easy to implement, and the response speed is very fast. However, in the charging and discharging driving process, since the driving signal is always effective, the current in the circuit will completely depend on the hardware parameters of the circuit itself, and generate a large peak current, which has a large influence on the circuit and reduces the reliability of the system.

2. Fixed duty cycle PWM control signal realizes multi-peak current drive mode, which can effectively limit the maximum current peak value, and realizes the control of driving circuit loop current by software. However, the fixed duty ratio has also greatly inhibited the response speed of piezoelectric actuators.

3. The variable duty cycle PWM control strategy based on current feedback realizes the approximate trapezoidal current charging mode, which not only has faster charging and discharging speed, but also can effectively limit the maximum current. The charging and discharging process is stable. Therefore, in terms of driving effect, the variable duty cycle PWM drive control strategy is optimal among the three control strategies.

References


