

Impact of Control Methods on Dynamic Characteristic of High Speed Solenoid Injectors

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ABSTRACT

Accurate control of both the timing and quantity of injection events is critical for engine performance and emissions. The most serious problem which reduces the accuracy of the control operation in such systems is a time delay of the responsiveness for the opening and closing operation of the electromagnetic valve. Modern electronic control systems should be capable of driving high speed solenoid injectors at a very fast switch frequency with high efficiency and acceptable power requirements. In this paper, the dynamic characteristic of a high speed servo-hydraulic solenoid injector for diesel engine, with different driving circuits and control methods, is investigated. A pre-energizing control strategy based on a dual power supply is applied to speed up the opening response time of the injectors. The effect of free-wheeling circuit on the closing response time is experimentally studied and a reverse-energizing circuit is utilized for achieving a rapid extinction of the operating magnetic field. The solenoid current is measured to get the electrical delay of the injectors. Meanwhile, high-speed photography is employed to detect the total delay (electrical delay, hydraulic delay and mechanical delay) of the injection spray process. The results show that, there is a high correlation between the opening delay and the solenoid current, but the armature of the injector will not move until the current reaches a threshold value. The switching time (both the opening and the closing time) could be further optimized through the proposed driving circuits and control strategies without any change to the injectors. As a result, the interval between two injections can be significantly reduced, which can provide greater flexibility for multi-injections strategies.

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INTRODUCTION

Direct injection technology has provided a highly precise and flexible method to optimize the emissions and efficiency of the piston engine, including diesel engine and gasoline engine. With increasingly stringent CO₂ and noxious emission regulations, the number of injection events in a single combustion cycle has also increased, about 2~3 times in gasoline direct injection (GDI) engines and 3~8 times in diesel engines. These trends demand a more rapid and precise response of the high speed solenoid injector. The response delay of the injector is inevitable during its opening and closing period. Because the solenoid injector is an inductive element. Solenoid valve injector along with the development of Engine electronic control technology has made great strides in the past few decades. The control methods of the solenoid valve injector have also been upgraded with the progress of the electronic component. In 1971, Motorola Inc. had used transistors to control the opening and closing of the solenoid valve [1]. The Bendix Corporation applied for a patent about inductive drive circuit in 1979, which had initially formed an idea of close-loop control on the current of the solenoid [2]. From 1981 to 1985, several companies such as Bosch, Lucas,

Denso, and Ford etc. invented different methods and apparatuses for driving the solenoid injectors, which had almost the same core idea of "Peak & Hold" current control method [3, 4, 5, 6, 7]. This idea applies a high-amperage current to solenoid injectors at the beginning of a trigger pulse, which is called "Peak" stage. Once the solenoid valve is opened, no other mechanical work needs to be performed, and therefore a smaller current is sufficient for maintaining the open position of the valve than is required for opening the valve itself, which is called "Hold" stage. "Peak & Hold" method has undoubtedly become a basic idea of driving the solenoid injector ever since, for it can not only make the current in the coil of the solenoid rise sharply, but also reduce the power consumption and keep the injector from overheating.

In addition to speeding up the opening process, engineers were also laying emphasis on minimizing the closing delay. As the solenoid injector is an inductive load, the freewheeling circuit was employed to smooth the current and eliminate the sudden voltage spike across an inductive load when its supply voltage is suddenly reduced or removed. This circuit works when the Pulse Width Modulation (PWM) is used to control the power supplied to the coil of the solenoid. While during the

closing process, the freewheeling circuit will also slow down the extinction of the electromagnetic field in the coil, which leads to the closing delay. From 1985 to 1996, Denso, Motorola, Chrysler, Caterpillar, and Honda etc. applied for their own patents of solenoid injector driving circuits with the freewheeling control functions, which can get a fast decay path to allow the solenoid valve to return to its inactivated position [8, 9, 10, 11, 13]. After that, during 1997 to 2008, the MOSFET technology had made considerable progress, so that companies like Mitsubishi, Bosch, Toyota, Conti and Delphi applied MOSFET to replace traditional transistors to reaching higher power efficiency and the system was greatly simplified. Thus the mainstream solenoid injector driving circuit has finalized the design [14, 15, 16, 17, 18, 19].

Even though automobile manufacturers have kept refreshing their driving circuits for high speed injectors, there are rarely few elaborate investigations about the impact of control methods on the dynamic characteristic of high speed solenoid injectors, especially the switching delay. Mooney, Jrohn D (2003) establishes a process for evaluating parameters of the driving circuits via simulation [20]. Then SONG Jun (2005) BB further investigated the opening pulse and PWM pulse duty factor of the driving circuits, and found that an ideal control current can be achieved by optimized parameters [21]. Lee, Ill-Yeong (2006) designed an electronic valve driving circuit with 3 power source, which can shorten the switching delay time from 5 ms to 1.55 ms [22]. Afterwards, Ziqiang Xu simulated the driving circuit of solenoid valve employing a precise PSPICE model, which applied a method of high and low side driving. The result turned out that the model could achieve the current driving requirement of solenoid valve [23]. Huang Du (2011) designed drive circuits for a GDI injector, and verified that the drive circuits satisfied the requirements through detecting the current waveform [24]. More recent studies by Sheng-Nian Cai (2012) used soft switching technology in high speed solenoid valve driver circuit, and found it can reduce switching losses and noise. The energy consumption of the injectors could be further improved [25].

These previous researchers have provided many advanced control methods to satisfy the current requirement of solenoid injectors. However, the data of the total opening and closing delay of the injection behaviors are still scarce. Considering the fact that multi-injection strategies are becoming more and more complex and precise, the crank angle would the fuel be exactly delivered to the cylinder after the injection pulse had been given are really cared about. On the other hand, many different control methods have been proposed, and further comparison studies are still necessary.

The purpose of this paper is to investigate the impact of different control methods on the dynamic characteristic of the injection events, and the paper will only focus on the mainstream solenoid injectors, which has a better technological maturity and cost efficiency than the piezo injectors. Based on the common rail and high speed imaging system, the spray characteristics are investigated in a constant volume vessel.

The spray characteristics are compared to check the effects of different driving voltage, opening strategy, power supply mode and cut-off strategy. Meanwhile, the current of the injector is also detected and compared with the spray characteristics.

EXPERIMENTAL FACILITIES

Variable Driving System

In order to meet the test requirements, a specially designed driving circuit for the solenoid injector is employed. The Variable Driving System, showed in Figure 1, can operate in multiple modes. All the possible current paths are marked from "a" to "e". The flexible control strategies can be achieved through the combination of different paths. There are 5 MOSFETs (Metal-oxide-semiconductor field-effect transistor) in this circuit, working as switch components. Among them, H1, H2, H3 are high side switches and L1, L2 are low side switches. All the MOSFETs are integrated with body diodes and 2 discrete diodes are used in path "a" and "b", which can turn the path into "one-way streets". HV (High Voltage) is supplied by a boost circuit and the HV can vary from 40 V to 100 V. LV (Low Voltage) is a 12 V battery. All the MOESFETs are controlled by PWM (Pulse Width Modulation) signal generated from a MCU (Micro Controller Unit). It's worth noting that the MCU cannot drive the MOSFETs directly, so there are still some circuits between the MCU and the MOSFETs. To drive the high side MOSFETs, the bootstrap circuit is recommended.

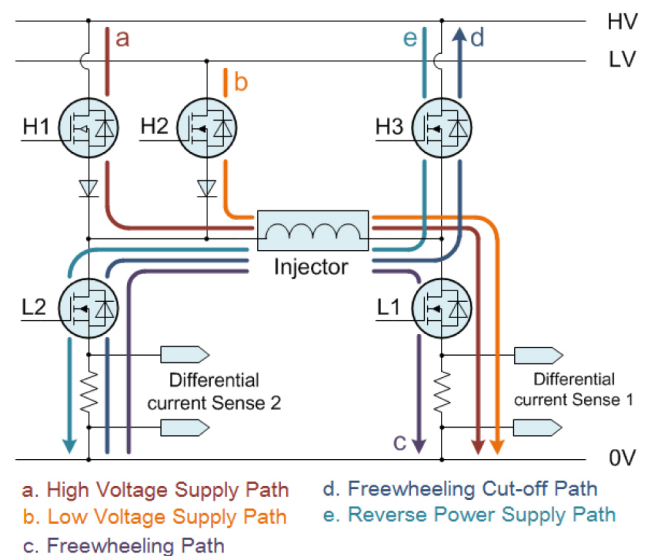


Figure 1. Schematic diagram of the Variable Driving System

As Figure 1 shows, when H1 and L1 are turned on, HV is supplied to the solenoid injector through path "a" and the coil will have a higher current. When H2 and L1 are turned on, LV is supplied to the injector through path "b", and the current will be lower than path "a". As the solenoid is an inductive load, the H1 or H2 can rapidly switch on or off, which called PWM mode, to control the current in it. During this PWM period, when H1 and H2 are both in non-conducting states, current generated

by the self-induction effect will flow through path “c”, which is always called the freewheeling circle. If the L1 is suddenly cut off during the freewheeling period, the self-induction voltage of the injector will have no way to go, except the path “d”. Path “d” can not only provide the discharge channel of the inductive voltage, but also can recycle some energy of the solenoid and improve the efficiency of the system. The last path “e” will not work until the L2 and H3 are turned on. The current will flow in the reverse direction, which is supposed to accelerate the extinction of the electromagnetic field in the solenoid when the injector is closing. Differential current sense 1 and 2 are used to real-time monitor the current of the injector, which can provide the conditions for the closed-loop control.

Spray Characteristics Test System

The spray injection delay characteristics test bench includes a common rail system, a constant volume, a laser generator, a high speed camera and an injection control system. The common rail system can provide injection pressure up to 150MPa. The constant volume, which is filled with nitrogen, can operate at the highest back pressure of 5MPa. The test bench configuration is illustrated in Figure 2. The high speed complementary metal oxide semiconductor (CMOS) camera (Phantomv7.3) equipped with a 105 mm focal length Nikkor lens is used in this study, and the images are collected at 33,000 fps, 28 μ s exposure time, and with 192 $\times$ 360 pixel resolution.

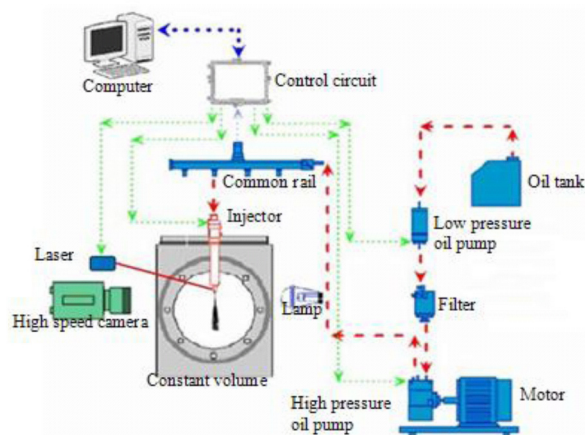


Figure 2. High pressure common rail spray test bench

The solenoid valve injector is driven by ECU. When ECU sends out the injection signal to the injector, another synchronous signal is sent out to the laser generator and then the laser generator emits a laser beam, pointing to the head of the injector. Then the high speed camera is utilized to record the laser signal and the whole spray injection process: the laser signal first appears and then the spray comes out from the nozzle tip; the laser signal disappears and then the spray departs from nozzle tip. In that case, the interval between the injection signal and the real injection can be calculated. The Figure 3 shows the whole recording process. The delay of the laser, from the given electrical signal to optical signal appears, is less than 1 μ s. While the delay of the injection is about hundreds of microseconds to milliseconds, so the laser delay is small enough to be ignored.

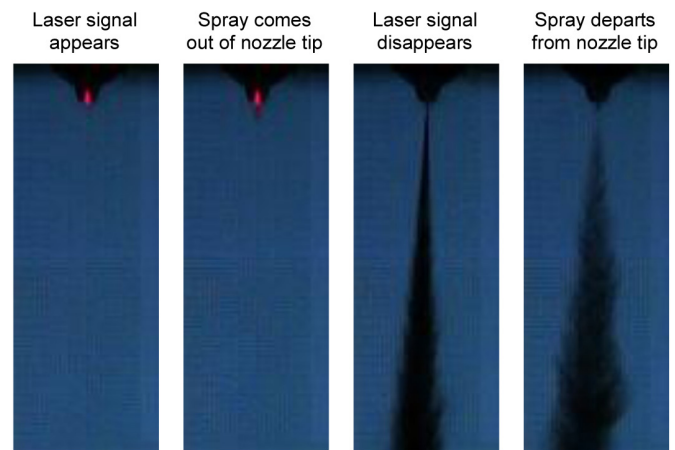


Figure 3. Laser signal and spray injection process

Parameters Definition

Injection Delay Parameters Definition

In this article, the time interval between ECU sending out a “start injection” signal and the actual injection beginning is defined as Injection Opening Delay (IOD), which in pictures reflects the time interval between the laser signal appearance and the fuel injecting out of nozzle tip. The Injection Closing Delay (ICD) is defined as the time interval between ECU sending out an “end injection” signal and the actual injection ending, which correspondingly in pictures equals to the time interval between the laser signal disappearance and the injection fuel departs from nozzle tip. The Set Injection Duration (SID) is defined as the time interval between the laser signal appearance and its disappearance; and the Real Injection Duration (RID) is the time interval between the spray coming out and departing from nozzle tip. The relationships between these parameters are shown in Figure 3.

Spray Characteristics Parameters Definition

Parameters of the spray tip penetration (S) and the spray cone angle (θ) are normally chosen by researches to present the spray features. As presented in Figure 4, the spray cone angle is the largest angle formed by the two boundaries of spray and the nozzle within the calculation range.

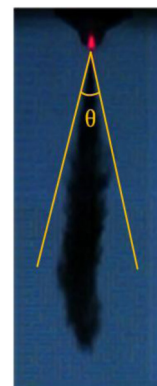


Figure 4. Definitions of spray core angle