Drive Control Simulation and Experimental Studies on the Flow Characteristics of a Pump Injector

HAOCHENG JI, MINXIANG WEI, RUI LIU, AND CHENG CHANG

1 College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
2 Jiangsu Province Key Laboratory of Aerospace Power System, Nanjing University of Aeronautics and Astronautics 210016, Nanjing, China
3 School of Mechanical and Power Engineering, Nanjing Tech University, Nanjing 211816, China

Corresponding author: Minxiang Wei (weimx@nuaa.edu.cn)

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ABSTRACT As a miniaturized direct injection (DI) solution, the pump injector is of great significance for small aviation piston engines, such as two-stroke heavy-fuel engines. The accurate control of the timing and amount of injections is an important application prerequisite. In this paper, the flow characteristics of a pump injector with different driving circuits and parameters are investigated. The effects of the power supply and freewheeling circuits on the opening and closing delays are theoretically studied. A schematic of a self-designed logic control circuit is proposed, and it achieves peak and hold current control without software intervention. Simulations and experiments are carried out, and the drive current and flow characteristics in different states are measured. The results show that when driving a solenoid with a high internal resistance of 2.70 Ω, a single power supply is more suitable, and the variable-freewheeling circuit exhibits excellent performance in terms of control accuracy and energy recovery. Notably, the invariable-freewheeling circuit results in nonlinear flow characteristics, and the nonlinear segment corresponds to the drive current transitioning from the peak value to the hold value. In contrast, the variable-freewheeling circuit overcomes this problem. To comprehensively consider solenoid opening and closing delays, energy consumption and the linearity of the flow characteristics during injection, a peak current of 10 A and a hold current of 8 A are adopted.

INDEX TERMS Aviation aircrafts, direct injection, flow characteristics, peak and hold drive, piston engine, pump injector.

I. INTRODUCTION Small aviation aircrafts powered by piston engines are becoming increasingly popular in civil and military fields [1]. Due to safety issues related to fuel storage and transportation, gasoline is replaced by heavy fuels such as light diesel and aviation kerosene due to their high flash point, low volatility and high energy density [2]. Direct injection (DI) technology was introduced to increase power output and reduce fuel consumption. Many studies have investigated the effect of DI parameters on heavy-fuel engine performance and emissions using high-pressure common rail systems for vehicles [3]. The common rail solution provides an extremely high fuel pressure, but the mechanical system is too complicated to miniaturize. There are certain DI solutions dedicated to aviation piston engines, and the most well-known solution is Orbital air-assisted direct injection (AADI), which provides a high-quality spray with compressed air at a pressure of 0.6 MPa [4]. Many experimental and numerical studies are based on the AADI technology [5]–[12]. Garipov et al. point out that the injection pressure in AADI is too low to achieve late injection and thus proposed an improved compressed air atomizer (CAA) with an injection pressure of 5.5 MPa [13], [14]. AADI solutions require a mechanical air compressor driven by the engine, and the alternative self-pressurizing pump injector solution, which has a moving coil inside to...
pressurize the fuel before injection, seems simpler and has an injection pressure that can reach 5 MPa [15]. Fig. 1 shows the schematics of the two injectors.

FIGURE 1. Schematic of the AADI injector (a) and pump injector (b).

In contrast to saturated drivers for fuel or air injectors with high-resistance coils in AADI, pump injectors have lower-resistance coils and need a peak and hold driver [16]. Studies have examined the use of pump injectors on engines, but the forms and parameters used to drive injectors are usually not mentioned. This paper analyses the influence of drive parameters and circuits on injector operation. The peak and hold drive is a basic idea for all solenoid injectors because it allows the current to rise sharply with a high-voltage (HV) drive, reduces power consumption and keeps the injector from overheating at a low voltage (LV). There are many related studies. For example, Yamakado et al. designed an injector with a dual-coil structure with opening and holding coils corresponding to the peak and hold stages, respectively.

The injector could be driven by battery voltage, and the drive circuit is compact and does not produce magnetic noise [17]. Chen et al. also developed a dual-coil fuel injector, but its main purpose was to lower power loss and achieve a faster dynamic response [18]. Mooney proposed a simulation methodology for analysing a self-designed injector driver [19]. Pilato et al. analysed a typical configurable inductive load driver chip that is available on the market and designed an alternative system based on an optimized and flexible architecture to shape the current waveform into loads with regulation feedback and a programmable solution [20]. Infineon offered a solution for generating a current shape with the 32-bit TriCore derivative TC1775 [21]. Huang et al. designed a solution similar to that of Infineon but added hysteresis and logic output control circuits to reduce the complexity of the MCU program [22]. Li et al. implemented a three-stage peak and hold current drive by a self-designed feedback control hardware circuit to minimize the complexity of the software, but only the circuit schematic was provided instead of the actual circuit [23]. Tsai et al. designed a more complex three-stage drive circuit with three low-side drive controls and tested it on a Bosch injector. The driving circuit board shown was approximate and complicated [24]–[26]. Kumat et al. used solutions similar to those of Tsai et al. and analysed the performances of the power MOSFET, IGBT and power transistor via simulations in Multisim [27]. Lu et al. designed a variable drive system that could be used to comprehensively study the effects of different control strategies (driving voltage, opening and closing strategies and supply voltage) on the opening and closing delays of injection events with a high-speed imaging system [28]. Liu et al. designed a variable-freewheeling circuit that exhibited a higher control accuracy, lower electric energy consumption and less heat release than those of the RD freewheeling circuit [29].

FIGURE 2. Peak and hold electronic circuit of the high-side modulation mode (a) and the low-side modulation mode (b).
The most common peak and hold current control circuit is shown in Fig. 2 (a) shows the high-side modulation mode, which is controlled by switching of the high-side MOSFET QH2, and the mode shown in Fig. 2 (b), which is the opposite of the mode in Fig. 2 (a), is controlled by switching of the low-side MOSFET QL. In low-side modulation, QH2 can be eliminated to reduce costs, but the shunt resistor needs to be placed on the high side, and the current sensor amplifier needs to withstand a common mode voltage equivalent to HV. Therefore, the high-side modulation mode is more common.

To eliminate the induced voltage of the coil, a freewheeling circuit was employed to slow the current drop [28]. The freewheeling circuit can reduce current fluctuations at the hold stage, but it causes a closing delay in the end stage, and solutions are shown in Fig. 3 (a) shows Delphi’s solution [19], namely, there is no detailed freewheeling cut-off circuit, but a reverse voltage is applied to the injector at the end stage according to voltage curves. Fig. 3 (b) shows Infineon’s solution in which a Zener diode D2 is added, and the induced voltage is released to the gate drive circuit at the end stage only [21]. The solution in Fig. 3 (c) efficiently minimizes the closing delay and recovers the freewheeling energy [28] since the freewheeling circuit changes during the different driving phases; this system is also called variable freewheeling [29]. Previous solutions addressed high- and low-side drives with high-side modulation, and the solutions for low-side drives are shown in Fig. 3 (d) and (e); although the whole circuit is much simpler, unchangeable freewheeling circuits are present and higher heat generation occurs [24]. In this study, the solutions of Fig. 3 (c), (d) and (e) will be considered.

In addition to the driver circuit, there is a logic feedback control circuit that modulates the state of high- or low-side MOSFET to attain an average current in the fuel injector according to the signal of the current sensor. There are three forms: entirely or partially relying on high-performance multi-core microcontrollers with high-speed analogue to digital conversion, with all control logic performed in the microcontrollers, such as Infineon’s solution with the TriCore derivative TC1775 [21], [22]; and using application-specific integrated circuits controlled by serial peripheral interface (SPI) communication, such as chip L99SD01-E of STMicroelectronics [20]. The latter is built with discrete components and controlled by the analogue injection signal [28], [29].

This paper intends to study the driving characteristics of pump injectors and apply them to small two-stroke DI aviation engines. The control module needs to be simple, effective, reliable and inexpensive. Therefore, multiple drives and freewheeling circuits must be compared and selected based on performance and price. Moreover, a logic feedback control circuit is designed with discrete components to minimize the controller performance requirement. Flow characteristics curves are obtained via experimentation to verify the control module and analyse the injection.

II. PUMP INJECTOR DRIVE SYSTEM BASICS

A. PARAMETERS OF THE PUMP INJECTOR

The electrical parameters of the pump injector are the basis of the drive. The solenoid can be represented as an inductor and resistor connected in series, and it can be tested with an LCR analyser. Another important parameter is the threshold current. When the injector is opening or closing, the movement of the armature causes an inductance change, which affects the current trend, and the corresponding current is the threshold current. The injector is manually driven for approximately one second, and the current rise and fall waveforms are recorded with an oscilloscope and a current probe. Moreover, the sampling frequency should be higher than 10 MHz for accurate details. Fig. 4 shows that the threshold current is
approximately 5 A since the current fluctuates at that value. For the sake of simplicity, the peak current is temporarily doubled, and the hold current is maintained slightly above the threshold current. The parameters are listed in TABLE 1.

### TABLE 1. Pump injector parameters.

| Parameter       | Value        |
|-----------------|--------------|
| Resistance      | 2.70 Ω       |
| Inductance      | 2.55 mH at 100 Hz |
| Peak Current    | 10 A         |
| Hold Current    | 6 A          |

#### B. EFFECT OF HIGH VOLTAGE VALUES

The injector opening delay is the basis of the drive and related to the HV value, and theoretical analysis would help in the selection of the appropriate parameter. The ideal injector model is the series connection of inductor L and resistor R, with the step voltage U input response of current I defined as follows:

$$I = \frac{U}{R} \cdot \left(1 - e^{-\frac{Rt}{L}}\right)$$  \hspace{1cm} (1)

Current curves at different voltages are shown in Fig. 5. The higher the driving voltage, the faster the current rises, but we care more about the time required to reach the peak current. By transforming equation 1, we can obtain:

$$t = -\frac{L}{R} \cdot \ln \left(1 - \frac{I_{\text{Peak}} R}{U}\right)$$  \hspace{1cm} (2)

#### FIGURE 5. Effects of the voltage on the solenoid current.

Considering a peak current from 8 to 16 A, the time required to reach the peak current changes with the voltage, as shown in Fig. 6. The figure is divided into three parts by two dashed lines with slopes of 0.004 and 0.016. In the upper part, small voltage variations have a very large impact on the required time, while in the lower part, voltage changes have little effect. Therefore, the appropriate voltage should occur in the middle part, and a range of 50 to 80 V is suitable according to the target peak current.

#### FIGURE 6. Effects of voltage on the time required to reach the peak current.

#### C. EFFECT OF FREEWHEELING

The closing delay of the target injector is related to freewheeling, and the freewheeling path can protect the drive circuit and affect the current drop rate. The freewheeling current without a cut-off can be expressed as:

$$I = I_0 \left(e^{-\frac{Rt}{L}}\right)$$  \hspace{1cm} (3)

Current curves with an initial value ranging from 4 to 8 A are shown in Fig. 7, and they decrease very slowly, which is appropriate at the hold stage for reducing current fluctuations but will increase the injector closing delay in the end stage of injection.

#### FIGURE 7. Freewheeling without cut-off.

The series resistance $R_F$ in the freewheeling circuit, as shown in Fig. 3 (d), can accelerate the current drop. The current curve and the time required for the initial current $I_0$ to reach the target current $I$ are as follows:

$$I = I_0 \left(e^{-\frac{(R+R_F)t}{L}}\right)$$  \hspace{1cm} (4)

$$t = -\frac{L}{(R + R_F) \cdot \ln \left(\frac{I}{I_0}\right)}$$  \hspace{1cm} (5)

By setting the target and initial currents to a fixed ratio (0.1 to 0.001), the time required is related to the freewheeling resistor only, as shown in Fig. 8. For an injector closing delay of less
than 0.5 ms, a resistance of at least 20 Ω is required, which results in high power and heat dissipation requirements of the resistor.

Another method for accelerating the current drop is to use a reverse voltage \( UV \). The current and the time required are as follows:

\[
I = I_0 - \frac{(U_V + I_0 R)}{R} \left(1 - e^{-\frac{R}{L}}\right) \quad (6)
\]

\[
t = -\frac{L}{R} \ln\left(1 - \frac{I_0 R}{(U_V + I_0 R)}\right) \quad (7)
\]

Current curves with initial values ranging from 4 to 8 A are shown in Fig. 9, and for an injector closing delay less than 0.5 ms, a reverse voltage of at least 25 V is required.

Reversing the HV power supply to drive the injector can minimize the closing delay but requires extra circuits and precise control. Variable-freewheeling circuits, as shown in Fig. 3 (c), have the same effect but are simpler. For a single high- or low-side drive, a reverse voltage can be obtained by the clamping voltage of the transient voltage suppressor (TVS) diode, as shown in Fig. 3 (e).

The current signal on the shunt resistor \( R_s \) is filtered and input to INA203. The output signals of the comparators switch according to current \( I \) and the voltage dividing resistors \( R_{st} \) and \( R_{sb} \) as follows:

\[
(I \times R_s) \times 20 V/V \times R_{sb} / (R_{st} + R_{sb}) = 0.6 V \quad (8)
\]

With a shunt resistor \( R_s \) of 10 mΩ, the above equation can be simplified to:

\[
R_{st} / R_{sb} = I / 3 - 1 \quad (9)
\]

The microcontroller outputs a fuel injection control pulse signal Inj_Signal. Comparator 1 yields a peak current signal Inj_Peak and latches by Inj_Signal. Comparator 2 outputs a hold current signal Inj_Hold. Based on the three output signals, the configurable gate produces the modulated signal Q_Modulation.

### III. SIMULATION AND ANALYSIS

#### A. DESIGN OF THE LOGIC CONTROL CIRCUIT

With the basic information of the pump injector, simulations are performed in Multisim for further analysis. Fig. 10 shows the self-designed logic feedback control circuit for the peak and hold current drive. The current sensor amplifier INA203 has dual comparators with an analogue output, one of which includes a latching capability. The configuration gate SN74LV1C1G58 is flexible, and its output state is determined by eight modes of 3-bit input.
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C. EFFECT OF FREEWHEELING

Fig. 13 shows the simulation circuits for a resistor in series with diode (RD) and TVS freewheeling at an HV level of 60 V, and a freewheeling resistance from 5–15 Ω and an SMPC15A freewheeling diode with a maximum clamping voltage of 24.4 V were selected. Due to the low-side drive, the position of the shunt resistor changes.

Fig. 14 shows the current curves of RD and TVS freewheeling and includes that of variable freewheeling as a reference. The current steadily drops in TVS freewheeling, but in RD freewheeling, it decreases exponentially and becomes extremely slow in the end. Increasing the resistance increases the current drop rate, but the breakdown voltage of QL and the common mode range of U1 need to be considered.

Fig. 15 shows the voltage on the drain electrode of QL, and the voltage in RD freewheeling is linearly related to the drive current. Even at a resistance of 4 Ω and a current
of 10 A, the peak voltage may reach 100 V, which would damage U1 and QL. The voltage in TVS freewheeling is stably controlled at approximately 80 V until the end, which occurs due to the clamping characteristics of the TVS diode. Therefore, TVS freewheeling is more suitable.

In summary, for a pump injector, the single-power supply mode is more suitable, and a drive voltage of approximately 60 V guarantees a proper injection opening delay at a reasonable cost. Considering the voltage effect on the QL drain gate, the injection closing delay of TVS freewheeling is significantly better than that of RD freewheeling but still not comparable to that of variable freewheeling. Since TVS freewheeling has a simpler circuit and variable freewheeling has a better effect, both circuits are prepared for experimental comparison.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. EXPERIMENTAL CONDITIONS

The experimental setup for the current measurement and flow characteristics test is shown in Fig. 16. The pump injector is mounted on the end of an acrylic tube through an aluminium bracket, and a measuring cylinder is located at the other end. There are two self-developed electronic control units (ECUs) for comparison, and they are connected to the injector via a harness. The drive current on the harness is measured by a Tektronix MSO2012 oscilloscope and a TCP0030 current probe. The other equipment parameters are listed in TABLE 3.

The initial peak and hold currents are set to 10 and 6 A, respectively. The captured current waveforms shown in Fig. 17 are basically the same as the simulated waveforms, but a longer time is required for the current to rise and less time is required for the current to drop. Considering the resistance and inductance of the harness, these changes are reasonable.

To compare the two freewheeling circuits and determine the appropriate peak and hold currents, 8 groups of injection flow characteristics were obtained.

B. EFFECT OF THE FREEWHEELING CIRCUIT ON THE FLOW CHARACTERISTICS

Tests 1 to 6 were conducted to compare the effects of the two freewheeling circuits on the flow characteristics, as shown in Fig. 18. It should be noted that the maximum fuel injection pulse width is limited to 2 ms because the TVS diode would overheat at a larger pulse width.

![Table 2: Experimental equipment parameters.](image-url)

![Figure 17: Drive current of schemes 1 (top) and 2 (bottom).](image-url)

![Figure 18: Flow characteristics of tests 1 to 6.](image-url)
| Circuits          | Peak current | Hold current | Test |
|------------------|--------------|--------------|------|
| TVS freewheeling | 6            | 6            | 1    |
|                  | 10           | 6            | 2    |
|                  | 10           | 10           | 3    |
| Variable freewheeling | 6          | 6            | 4    |
|                  | 10           | 6            | 5    |
|                  | 10           | 10           | 6    |
|                  | 10           | 4            | 7    |
|                  | 10           | 8            | 8    |

There are two common characteristics for the two circuits according to the flow characteristic curve. The first common characteristic is a peak current that increases from 6 to 10 A, which reduces the injector opening delay by 0.2 ms. The second common characteristic is that increasing the hold current increases the injection rate, which is a pump injector characteristic and can be explained by the higher hold current providing a larger force in the moving coil to increase the pressure in the pressure chamber.

There are three different characteristics. The minimum pulse width required for fuel injection differs by 0.1 ms under all three conditions, and it is directly related to the current drop rate at the end of the injection. The current drop delay difference is 0.3 ms according to Fig. 17. A slight decrease in current drop rate corresponds to a large injector closing delay, and more fuel is sprayed; therefore, the required minimum drive pulse width is smaller.

There is also a difference in the fuel injection rate, and the variable-freewheeling circuit has a higher injection rate that is more notable with a 6 A hold current. Fig. 19 shows the currents of the two circuits at the hold stage, and the current rise rate is consistent, but the drop rate in TVS freewheeling is higher. Therefore, the fluctuation range is larger, and the average current is lower. As mentioned, a lower hold current corresponds to a lower injection rate. When the hold current is 6 A, the lower boundary of the current is close to the threshold current, which affects injection. Therefore, the fuel injection rate will also be affected and is much lower.

It is also observed that when the injection pulse width is smaller than 1 ms, the flow characteristics of test 2 are highly nonlinear, which can be explained by the current waveform. Fig. 17 shows that in TVS freewheeling, the driving current transition occurs from 0.75 to 0.9 ms from the peak stage to the hold stage. If fuel injection ends during this time, then the current waveform remains unchanged due to the invariable freewheeling circuit, which can be confirmed by the measured current curve of test 2, as shown in Fig. 20. The same drive current waveform results in the same amount of fuel injected, which is the cause of the nonlinearity of the flow. Increasing the current drop rate can reduce the length of the nonlinear segment, but it cannot be eliminated. The use of variable freewheeling can completely avoid this nonlinear segment with the freewheeling parameters varying at the different stages, as revealed by the current curve of test 5 in Fig. 20.

![FIGURE 19. Current fluctuations at the hold stage.](image)

C. EFFECT OF DRIVE PARAMETERS ON THE FLOW CHARACTERISTICS

According to the analysis above, the variable-freewheeling circuit has more advantages and is more suitable for pump injectors. The next step is to determine the appropriate peak and hold currents. The internal resistance of the pump injector is much higher than that of a conventional DI injector; thus, it is desirable to reduce the drive current while ensuring that the injector opening delay is short and the flow characteristics are linear. Tests 4 to 8 were conducted to determine the appropriate driving parameters. The maximum injection pulse width was increased to 3 ms, and the flow characteristic curve is shown in Fig. 21.

Tests 4 and 5 show that a high peak current can reduce the opening delay, but there should be an upper limit. The pump injector requires approximately 0.75 ms to reach a peak current of 10 A, while fuel injection requires a minimum pulse width of 0.8 ms, which means that the 10 A peak current is already high enough. Test 7 demonstrates that although
injection starts with a peak current of 10 A, a hold current of 4 A cannot maintain the state. Test 4 indicates that despite the opening delay, a current of 6 A could start and maintain injection. Tests 4 and 7 reveal that the closing current threshold is approximately 5 A, which means that the holding current should be higher than 5 A. Tests 5, 8 and 6 reflect the flow characteristics of hold currents of 6, 8 and 10 A, respectively. Tests 6 and 8 show good linearity, and the injection rates are 10.22 and 8.42 g/s, respectively. To reduce heat generation and precisely control the amount of fuel injected, a hold current of 8 A is selected.

V. CONCLUSION

In this paper, the drive control effect on a DI pump injector is studied, the impacts of the drive parameters are analysed and a simple current modulation circuit is designed. After simulation and experimental research, the conclusions are as follows:

1) A higher HV level can reduce the injection opening delay, and an HV level of approximately 60 V is suitable. A higher HV level can also reduce the injection closing delay in variable freewheeling. The LV level needs to be at least 24 V to ensure a suitable hold current, and a single power supply simplifies the circuit while ensuring the same driving effect as that of the dual-power supply circuit.

2) To drive a solenoid with a high internal resistance, RD freewheeling can neither effectively reduce the closing delay nor control the voltage on the drain gate of QL. In contrast, TVS freewheeling may clamp the voltage, but the closing delay is still larger than that of variable freewheeling.

3) Invariable freewheeling will result in a nonlinear flow characteristic curve due to the drive circuit, and the nonlinear segment corresponds to the drive current transitioning from the peak value to the hold value, which can be reduced by optimizing the freewheeling parameters but is almost impossible to completely eliminate. Variable freewheeling avoids this problem and provides flow characteristics that are more linear.

4) The fuel pressure does not affect the flow characteristics, and increasing the peak current from 6 to 10 A reduces the injection opening delay by 0.2 ms. Furthermore, a peak current of 10 A is sufficient since the injector is fully open at this time. The opening and closing current threshold of the pump injector is approximately 5 A. A linear flow characteristic curve requires a holding current above 8 A. Increasing the hold current from 8 to 10 A can increase the injection rate from 8.42 to 10.22 g/s, but a lower hold current is preferred because it reduces heat generation in the solenoid.

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HAOCHENG JI received the B.S. degree in vehicle engineering from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2012, where he is currently pursuing the Ph.D. degree in power and mechanical engineering. His current research interest includes electronic control technology on two-stroke engines.

MINXING WEI received the Ph.D. degree from Xi’an Jiaotong University, Xi’an, China. He is currently a Professor with the Department of Vehicle Engineering, College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, China. He is involved in the research of automotive safety control technology and internal combustion engines.

RUI LIU received the B.S. and Ph.D. degrees in vehicle engineering from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2011 and 2017, respectively.

He is currently with the School of Mechanical and Power Engineering, Nanjing Tech University, Nanjing. And, he promotes relevant scientific research work with the Jiangsu Province Key Laboratory of Aerospace Power System, Nanjing University of Aeronautics and Astronautics. His current research interest includes the control and numerical simulation of direct injection internal combustion engines.

CHENG CHANG received the B.S. degree in vehicle engineering from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2013, where he is currently pursuing the Ph.D. degree in power machinery and engineering. His current research interests include the knocking combustion of internal machinery and engineering. His current research interests include the knocking combustion of internal combustion engines and knocking signal processing.