Influence of the control signal on parameters of low impedance injectors for SI engines

V Mihaylov\textsuperscript{1}, Z Ivanov\textsuperscript{1}, H Mersinkov\textsuperscript{1}, S Stoyanov\textsuperscript{1} and R Wrobel\textsuperscript{2}

\textsuperscript{1}Technical University of Varna, Department of Transport Engineering and Technologies, 9010 Varna, Bulgaria
\textsuperscript{2}Wroclaw University of Technology, Division of Vehicles and Combustion Engines, 50-370 Wroclaw, Poland

e-mail: v_mihaylov@tu-varna.bg

Abstract. There is high variety of injectors for spark ignited (SI) engines, especially those fitted with additional aftermarket LPG/CNG fuel system. The tendency is for using injectors with lower electrical resistance, because of the faster opening time. But this rise some difficulties, one of which is the higher current, that pass through injector’s coil. One of the most used method to counter fight that is using special control signal. Experiments are conducted with varying parameters of the control signal and its influence over current through the coil, temperature, injector’s opening and closing time. Results show that not only less current and heating of the coil but also faster operating speed of the injector itself can be achieved, as the modulation of the pulse affects mainly the closing time of the valve needle.

1. Introduction

A fuel injector is an electronically controlled solenoid valve (figure 1) which is controlled by the ECU. The main characteristic of an electromagnetic injector is the actual amount of fuel injected to the engine depending on the duration of the control signal. Studies show\cite{1,2,3} that as a result of electromagnetic processes, the movement of the valve’s needle within solenoid armature is out of phase with respect to the beginning and end of the control pulse. This dephasing depends on the design and characteristics of the electromagnetic injector, the magnetic properties of the armature and the resistance of the coil. In addition to these parameters, the duration of the closing time is significantly influenced by the shape of the control electrical signal\cite{4,5,6}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Section view of an LPG injector (a) and gasoline injector (b), \cite{1}:

- \textit{positions for a):} 1 – Nipple with calibrated orifice; 2 – Fuel rail; 3 – Rubber insert; 4 – Needle; 5 – Spring; 6 – O-ring; 7 – Coil.
- \textit{positions for b):} 1 - O-rings; 2 - Filter strainer; 3 - Valve housing with electrical connection; 4 - Current coil; 5 - Spring; 6 - Valve needle with solenoid armature; 7 - Valve seat with spray-orifice disk.}
\end{figure}
Figure 2 shows the control scheme for high impedance petrol injectors (10÷18 Ω), which are the most common in modern engines with port fuel injection. Low impedance injectors are used when there is a need for faster opening time - for example in throttle body injection systems. Another use of low resistance injectors is in CNG/LPG systems. The cross-section of these electromagnetic valves is significantly larger due to the supply of fuel in gas phase. In this way, the required fuel per cycle can be provided by injectors with larger valve needle and a significantly larger mass. The necessary magnetic forces to drive the armature of the electromagnet are obtained from low-resistance coils, whose electrical resistance is in the range of 1 Ω to 3 Ω.

A way to increase the speed of opening of the injectors is by providing more current through their winding. This can be obtained by a short-term increase in the voltage applied to the electromagnet, by analogy with common rail systems in diesel engines. An increase in the value of the current can also be obtained by reducing the impedance of the winding. The disadvantage of this method is that during continuous operation with a current higher than the nominal one, the temperature of the winding rises above the permissible values and the winding is overheated. To prevent this, once the armature is fully retracted, it is necessary to limit the current through the winding to a value which keeps the armature remains firmly attached to the core. A suitable way to limit the current through the injector winding is by using pulse width modulation (PWM) in part of the control signal - figure 3.
At the initial moment, the control transistor $T_1$ (figure 3) is switched on for a time equal to the time for opening the injector. At the same time, the second transistor $T_2$, which connects the freewheeling diode $D_1$, is also turned on. This diode is connected in parallel to the winding but in the opposite direction, i.e. no current flows through it while the control transistor is on. In the next stage, when the armature has reached the core and current limitation is required, the control unit starts sequentially switching off and on the control transistor with PWM signal with a constant frequency of about $10\div15$ kHz and a duty cycle between 30 and 60%, thus switching the current through the winding on and off and reducing its effective value. When the control transistor is switched off during the PWM, a self-induction current caused by the shrinking magnetic field is created in the solenoid winding. This current has the same direction as the operating current and continues to flow through the second transistor and the diode, which in this case turns out to be in the right direction. This causes the armature to be retained during the period in which the control transistor is switched off. At the end of the series of pulses, when it is necessary to close the injector fast, the second transistor turns off and disconnect the diode. As a result, at the last pulse the disconnection is by the method of interruption of current through the winding, and the characteristic increase of voltage is observed. The duration of different parts of this compound control signal influence the dynamic characteristics of the injector.

The aim of the study is to investigate how the control pulse affects various parameters of low-resistance injectors - opening time, closing time, current and temperature.

2. Experimental set-up

Figure 4 shows a diagram of the experimental setup. In the Labview software a program has been developed, with the help of which the digital-to-analog converter (DAC) - MCC 1208 (pos. 2) is controlled, which generates the control signals. These signals are fed to the amplifier (pos. 3), which controls the injector (pos. 7). The vibrations of the injector are measured using the accelerometer KD35, and the temperature - with the non-contact thermometer (pos.8). The digital oscilloscope (pos.5) records the data from: channel 1 - signal from the DAC; channel 2 - control signal to the injector; channel 3 - current to injector; channel 4 – vibrations. On figure 5 is shown the software for setting up parameters of the control signal. It has the ability to set the speed, duration of the whole control pulse, duration of the constant component of the pulse, frequency and duty cycle of the high-frequency PWM component of the pulse, generation time.

![Figure 4](image_url)  
**Figure 4.** Scheme of the experimental setup:  
1. – Computer, 2. – DAC, 3. – Amplifier, 4. – Accelerometer, 5. - Digital oscilloscope, 6. - Current clamps, 7. - Electromagnetic injector, 8. - Non-contact thermometer.
3. Results and discussions
The main parameters are obtained from the recorded oscillograms – figure 6. In all of the diagrams the channels are arranged in this way: ch1 – current; ch2 – vibrations; ch3 – voltage at the injector; ch4 – voltage of the generated signal. The maximum current and the regulated current are obtained by determining the voltage at the given points and multiplying by the range of the current clamps. The time for opening of the needle and closing can be determined by the vibrational pattern [7, 8]. The opening time is the time from the beginning of a pulse to the generation of vibrational signal. The closing time, respectively, is determined from the stopping of the pulse to the appearance of vibration signal.

3.1. Time parameters and current
For these studies is used an LPG injector Valtec with resistance 3Ω and needle lift 0.45mm. Modes of operation are as follows:
- Engine RPM - 1000min⁻¹;
- Pulse duration - 10ms, 15ms;
- PWM frequency - 5kHz, 2kHz;
- PWM duty cycle - 50% and 25%;
- Pulse type - with and without PWM;
- Flyback current: regulated, with and without diode.

Recorded signals at varying parameters of the pulse are shown on figures 6÷13. On table 1 are summarised the results from the experiments.

Table 1. Time parameters and current of injector Valtec 3Ω.

| No | Parameters of the signal | \( \tau_{\text{open}}, \) (ms) | \( \tau_{\text{close}}, \) (ms) | \( I_{\text{max}}, \) (A) | \( I_{\text{reg}}, \) (A) |
|----|--------------------------|-----------------|-----------------|-----------------|-----------------|
| 1  | 1000min-1 10ms 3ms+5kHz+50% | 3               | 2.6             | 1.6             | 1.2             |
| 2  | 1000min-1 15ms 3ms+5kHz+50% | 3               | 2.62            | 1.6             | 1.2             |
| 3  | 1000min-1 10ms 5ms+5kHz+50% | 3               | 2.62            | 2.3             | 1.3             |
| 4  | 1000min-1 10ms 3ms+2kHz+50% | 3               | 2.7             | 1.65            | 1.22            |
| 5  | 1000min-1 10ms 3ms+5kHz+25% | 3               | 2.48            | 1.65            | 0.85            |
| 6  | 1000min-1 10ms no PWM      | 3               | 2.84            | 2.5             | ----            |
| 7  | 1000min-1 10ms 5ms+5kHz+50% no flyback diode | 3 | -0.5 | 2.31 | 0.13 |
| 8  | 1000min-1 10ms 5ms+5kHz+50% with flyback diode | 3 | 6.62 | 2.3 | 1.22 |
**Figure 6.** Parameters of the pulse: $T_1=10\text{ms}; \ T_2=3\text{ms}; \ \text{PWM}\_\text{freq}=5\text{kHz}; \ \text{PWM}\_\text{duty}=50\%$.

**Figure 7.** Parameters of the pulse: $T_1=15\text{ms}; \ T_2=3\text{ms}; \ \text{PWM}\_\text{freq}=5\text{kHz}; \ \text{PWM}\_\text{duty}=50\%$.

**Figure 8.** Parameters of the pulse: $T_1=10\text{ms}; \ T_2=5\text{ms}; \ \text{PWM}\_\text{freq}=5\text{kHz}; \ \text{PWM}\_\text{duty}=50\%$. 
Figure 9. Parameters of the pulse: $T_1=10\text{ms}$; $T_2=3\text{ms}$; 
$\text{PWM\_freq} = 2\text{kHz}$; $\text{PWM\_duty} = 50\%$.

Figure 10. Parameters of the pulse: $T_1=10\text{ms}$; $T_2=3\text{ms}$; 
$\text{PWM\_freq} = 5\text{kHz}$; $\text{PWM\_duty} = 25\%$.

Figure 11. Parameters of the pulse: $T_1=10\text{ms}$; $T_2=10\text{ms}$; 
$\text{PWM\_freq} = 0\text{kHz}$; $\text{PWM\_duty} = 100\%$. 
Figure 12. Parameters of the pulse: T1=10ms; T2=5ms; PWM_freq =5kHz; PWM_duty =50%, Flyback diode off.

Figure 13. Parameters of the pulse: T1=10ms; T2=5ms; PWM_freq =5kHz; PWM_duty =50%, Flyback diode on.

The results show that the opening time does not depend on the type of pulse. The constant component of the pulse T1 usually is chosen so that it is a little longer than the opening time. If this period is increased, the current is going steeply up – figure 8. The current during the shim modulation depends largely on the percentage of filling of the pulse, it is also observed that this influence the closing time – figure 10. In case where no PWM is used (figure 11) the maximum current is around 56% higher than normal case, as well the closing time is also longer with 9%. Figure 12 and figure 13 show why the flyback diode should be controlled and it should be switched on during the PWM period and switched off at the end of the duration of the whole signal. In case when there is no flyback diode (figure 12) during the PWM signal the current is falling steeply and at some point the needle closes, although there is still control signal, that’s the injector closes prematurely. In case there is flyback diode switched on all the time, the current is falling slowly after the end of the pulse and it takes longer time for the needle to close – in our case the closing time is around 2.5 times longer.

3.2. Temperature
Figures 14 and 15 show the dependence of temperature of low and high impedance injectors at different parameters of the control signal.
When the low impedance injector is working at 3000 min\(^{-1}\) with PWM the maximum temperature in the area of its winding is 60 degrees after 5 minutes of work; in mode without PWM the injector reaches 90 degrees for 210 seconds. Therefore, we can conclude that the injector cannot operate without current regulation. At 6000 min\(^{-1}\) the same trend is observed as here 90 degrees are reached in 120 seconds, ie almost 2 times faster. Also, even with PWM, after 5 minutes the temperature is around 90 degrees, which means that it is not desirable to operate the injectors in this mode for a long time.

With the high-impedance injector there is practically no problem with the temperatures as the blue curve shows the operating mode with the injector constantly on - after 5 minutes the maximum temperature is only 60 degrees.

### 4. Conclusion

Performed studies have shown that the use of PWM of the control signal has the following advantages: reduces the current flowing through the injector winding; the heating of the injector is reduced; the closing time of the anchor is reduced, as this method of control does not affect the opening time. The conclusions can be summarized as:

1. Electromagnetic injectors with a resistance below 5\(\Omega\) cannot be controlled by a constant pulse due to the high temperatures that develop in the area of their coil.
2. PWM modulation of the control pulse is an effective method for reducing the current, and hence the temperature of the winding.

3. With the PWM modulation of the control pulse, a better speed of the injector itself is achieved, as the modulation of the pulse affects only the closing time of the valve needle, reducing this time by up to 12%.

4. It is necessary to use a controlled flyback diode in the control circuit, otherwise the closing time of the injector will be unnecessarily long.

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