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Evaluation of Applying Various High Voltage Levels to Improve Fuel Injector Response Time on Gasoline Engines

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Abstract: This paper presents the effect of various high applied voltage levels on the responsiveness of fuel injectors on gasoline engines. During operation, the inductance in the injector changes at a certain value because of the change of magnetic permeability, which is the result of the needle lifting process, directly affects the curve of the current in the needle. On the other side, the amperage in the injector is hampered by another amperage produced by the phenomenon of self-inductance, leading the current in the injector increase slowly resulting in the needle lifting will be delayed. Normally, there are two ways to increase the response time that including the improvement of fuel injector shape and injection control method. But in this paper, to improve the response time without changing either the structure or the control method of the injector, the authors conduct research on increasing the operating voltage level in order to reduce the dead time of the needle. In particular, a mathematical description of the fuel injector amperage will be built based on two different inductance values, then some experiments are practiced to evaluate the response time of the fuel injector. Experimental results in the range of 12V to 30V indicated that the sensitivity of the injector was significantly improved.

Keywords: EFI, Electromotive Force, Fuel Response Time, Inductance

1. Introduction

Currently, the electronic fuel injection system (EFI) plays an important role in the operation of the vehicle. When supplying 12V, the injector lifts and fuel is sprayed.

Due to the nature of the injector is constructed from the coil, when applying a constant voltage to the coil, the current will not increase in a straight line, but must slowly increase in a curve instead (figure 2). The reason is that when the injector is supplied with electricity, the self-inductance electromotive force in the injector tends to counteract the cause of its generation, so the current in the injector increases gradually until the magnetic force is greater than or equal to total drag is pressed against the company, at this point the piston injector will be lifted, fuel is ejected. Because of this, in ECUs controlling EFI systems in vehicles, manufacturers programmed to inject the fuel with a time t early to overcome the "delay" of the needle.

There are a number of studies on the fuel injector deadtime problem. Krzystof Wieclawski et al. [1] conducted current measurements in injectors with Hall sensor, then analyzed and simulated current and voltage current waveform. Dean Cvetkovic et al. [2] have modeled the injector in order to reduce the size and improve the needle response by making several hypothetical models of different profiles of the injector magnetic parts. Skowron et al. [3] assessed the external signals of fuel injection by piezoelectric injectors of engines fueled with gasoline and diesel fuel with the main purpose is to focus on the delay analysis of fuel injection start in relation to the time of appropriate control signals occurred. Abe et al. [4] developed a new injector for direct injection gasoline engines that reduce the exhaust emissions and help to reduce fuel consumption with two features including a bounce-less valve closing machenism and the quick response time. Yasukawa et al. [5] improved the anchor shape of gasoline fuel injector in order to decrease the hydraulic resistance of moving parts for quick response of moving parts. Guo et al. [6] develop a technique to measure the dynamic responding time of the electronic fuel injector (EFI) to to evaluate injectors and improve its design by the shape of amperage. The above studies have not mentioned changes in needle inductance during operation and improve needle responsiveness by different high voltage ranges. Therefore, in the scope of this paper, the authors conducts analysis of the injector's operation process and the change of inductance in the coil during the switching time. In addition, following the publication of the previous researches [7-13], this is the partial connection in the doctoral thesis which titled "Reseach, application self-inductance energy in automobile".

The article is written under the following structure. Section 2 presents the theoretical basis of injector operation. Section 3 presents the experimental results at different voltage ranges. Finally, section 4 summarizes the paper.

2. Theoretical Basis of Fuel Injector

Figure 1 below shows the basic construction of a fuel injector on a gasoline engine. When a voltage is applied to the coil, at a time the current in the coil is large enough to overcome the total resistance of the return spring and the fuel pressure, the needle is lifted, fuel is ejected. On the other hand, the piston in the injector is composed of a metallic material, and the displacement of the piston in the injector changes the permeability density of the medium between the two coil poles. In other words, when the plunger of the injector is lifted up, the inductance of the coil in the injector will change.

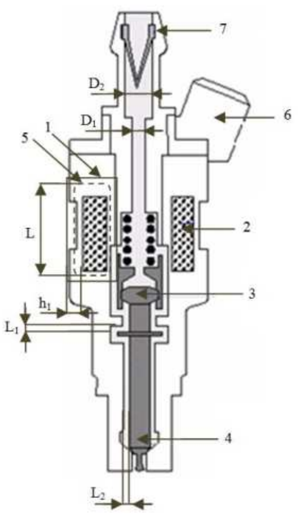

Figure 1. *Structure of fuel injector [14]: 1 – iron core, 2 – magnetic coil, 3 – Armature, 4 – needle, 5 – Nozzle-holder body, 6 – electric plug, 7 – filter.*

Called L is the self-inductance of the fuel injector, L is determined by (1).

$$L = \mu.\frac{N^2 A}{l} \tag{1}$$

Where N (turns) is the number of turns of the winding, A (m^2) is the cross-sectional area of the winding πr^2, l (m) is the length of the winding and μ is the magnetic permeability of the winding.

Armature part operation is divided into two phases. In stage 1, the armature is in the closed position, the space inside the coil is now purely air. At which point, the magnetic permeability of coil will be:

$$\mu_1 = \mu_{air} \tag{2}$$

In stage 2, when the armature part moves upward due to the magnetic force, the space inside the coil changes due to the presence of the armature component. At this time, the magnetic permeability in the coil will be greater than the initial value.

$$\mu_2 = \mu_{air} + \mu_{metal} > \mu_1 \tag{3}$$

On the other hand, the equation from (1), the quantities such as the number of winding turns, the cross-sectional area and the length of the winding are kept in constant during injectors operation. Therefore, when the armature in the injector moves up, the inductance L increases due to the increased inner permeability.

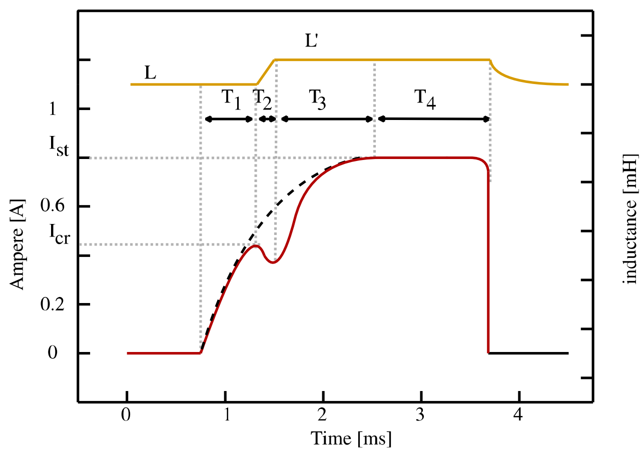

Figure 2. *The characteristic of current through the injector.*

In figure 2, when voltage is applied to the injector, the amperage in the coil begins to increase from 0A, until the electromagnetic force is greater than the total pressure applied to the needle, the injector is lifted. At this time, the electric current through the injector will have a small drop due to the increased inductance in the coil due to increased L. Then the amperage in the needle continues to increase until the saturation value is reached, which obeys Ohm's law based on the resistance and voltage of the needle.

The relationship between the characteristic curves of voltage and intensity follows (4) [15] below.

$$I = \frac{U}{R}(1 - e^{-\frac{R}{L}t}) \tag{4}$$

In which, U is a power voltage supply, R and L are the resistance and inductance of fuel injector respectively.

Called T_1 – dead time, calculated from the current increase from 0 to I_{cr} (figure 2). When the coil current increases to I_{cr}, the electromagnetic force is now greater than the difference of force acting between the compression force of the return spring and the fuel pressure, at which point the needle starts to move up, respectively, corresponding to the T_2 onset stage, until the end of stage T_2 is when the tympanum is completely lifted off the base. Next stage T_3, the current in the injector continues to increase until the saturation value is reached. Finally, at the stage of T_4, the current does not increase any more, keeping it in saturation. During T_2 + T_3, the injector moves inaccurately with the amount of fuel injected.

On the other hand, L_1 and L_2 are the inductance of the injector before and after lifting the needle respectively. We have $L_2 > L_1$ and the inductance value increases or decreases according to the law of the exponential.

$$L_2 = \frac{L}{e^{-t}} \tag{5}$$

$$\begin{aligned} \Delta L &= L_2 - L_1 \\ &= L_2(1 - e^{-t}) \end{aligned} \tag{6}$$

Consider the change of inductance in the injector in the needle lifting process into 3 main stages.

Stage 1 (T_1): needle closed, the inductance is L_1

At this stage, the amperage is increased corresponding to T_1 in figure 2. At this point, the magnetic force (F_m) in the injector is very low compared to the total resistance of the return spring (F_s). and fuel pressure (F_f).

$$F_f + F_s \gg F_m \tag{7}$$

The amperage in phase 1 is:

$$I_1 = \frac{U}{R}(1 - e^{-\frac{R}{L_1}t_1}) \tag{8}$$

Stage 2 (T_2): needle is going to lift up, the inductance starts to change from L_1 to L_2.

During this stage, the magnetic force overcomes the total resistance placed on the needle, and it begins to lift off the pedestal.

$$F_f + F_s = F_m \tag{9}$$

On the other hand, the inductance of the injector starts to increase from $L_1 \rightarrow L_2$, then the current will drop dramatically (dI/dt=0).

$$\begin{aligned} I_2 &= \frac{U}{R}(1 - e^{-\frac{R}{\Delta L}t_2}) \\ &= \frac{U}{R}\left[1 - e^{-\frac{R}{L_2 - L_1}t_2}\right] \\ &= \frac{U}{R}\left[1 - e^{-\frac{R}{L_2(1-e^{-t_2})}t_2}\right] \end{aligned} \tag{10}$$

Can be seen from equation (10), U and R are the constant values during the lifting of the needle, so the inductance increases suddenly and the current will decrease. However, the period of current falling is very short, because the t_2 value increases with time, leading to progression to L_2, at which time the amperage will continue to increase.

Stage 3 (T_3): needle is completely lifted, the inductance reaches L_2

At this stage, the magnetic force is greater than the compression of the spring and the pressure of the fuel. The needle has been lifted completely off the pedestal.

$$F_f + F_s < F_m \tag{11}$$

At this time, the inductance has reached the L_2 value, the amperage continues to increase until the saturation value is reached.

$$I_3 = \frac{U}{R}(1 - e^{-\frac{R}{L_2}t_3}) \tag{12}$$

Stage 4 (T_4): the amperage is saturated.

In the final stage of needle lifting, the amperage has reached a constant saturation value with time.

$$I_4 = \frac{U}{R} \tag{13}$$

Can be seen that during injector operation, the times T_1, T_2 and T_4 are constant, while T_3 changes depending on the calculation of the microcontroller. Therefore, to ensure the accuracy of the injection time as well as the injection time, the author investigates the different operating voltage levels of the needle with the aim of finding out the relationship between time T_1 and voltage operation.

3. Experimental Results

The author conducted experiments on fuel injectors DENSO 195500-3110, with structural parameters R=13.8Ω and L=0.03H.

Figure 3. *Fuel injector Denso 195500-3110.*

Nozzles are applied with operating voltages in range from 12V (standard) to 30V. Experiments are conducted in a laboratory under standard temperature conditions at 25°C.

The power supply for the injector is a Pintek PW-8033P pulse source. In addition, the Tektronix TBS 1052B EDU oscilloscope is used to measure the current waveform of the injector.

Figure 4 below shows a characteristic curve of the relationship between the operating voltage and the response time of the needle (T_1).

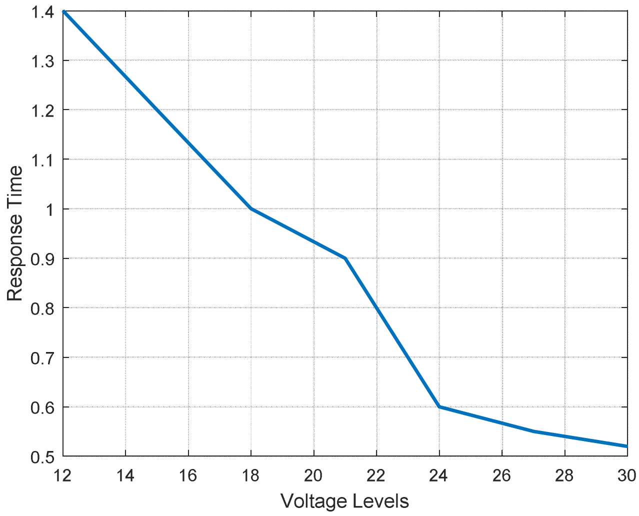

Figure 4. *Relationship between the voltage and response time of the injector.*

As can be seen from figure 4, the vertical axis corresponds to the response time of the needle, the horizontal axis corresponds to the voltage applied to the needle. Overall, the needle deadtime has been reduced from 1.4ms for 12V voltage to 0.52ms at 30V. The operating voltage of the needle is divided into 3 groups: group 1 includes voltages from 12V to 18V, group 2 from 18V to 24V and finally group 3 from 24V to 30V. In the first voltage group, the needle deadtime decreased linearly from 1.4ms to 1ms, with a gap is 0.4ms. Next, in the 2nd voltage group, the injector deadtime is reduced from 1ms to 0.6ms, the difference is 0.4ms similar to group 1. Finally, at the voltage of group 3, the time needle lift slightly decreased from 0.6ms to 0.52ms, with a difference of only approximately 0.1ms (figure 5).

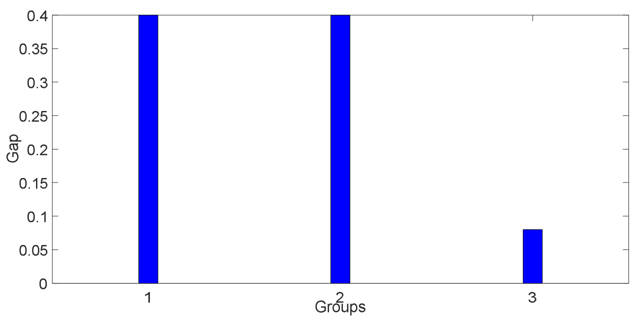

Figure 5. *Time difference of injector response of 3 voltage groups.*

In general, in two voltage groups from 12V to 24V, the injector sensitivity increases strongly with increasing electrical levels. In the third voltage group, the injector sensitivity is only slightly reduced. On the other hand, the higher the voltage, the higher amperage through the needle, corresponding to the increased needle heat. Therefore, the safe voltage area supplied to the injector to increase the needle sensitivity should be between 12V and 24V.

4. Conclusion

The author analyzed the needle operation process and explained about the change in needle inductance during operation, this change in inductance directly affects the intensity profile electric current in the injector.

On the other hand, the author has conducted experiments to improve the responsiveness of the injectors by different voltage ranges from 12V to 30V. Experimental results show that the most effective lift zone in the range from 12V to 24V corresponds to the downtime of the injector reduced from 1.4ms to 0.6ms.

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Biography

Phan Nguyen Qui Tam (1981, Thu Dau Mot city). After graduated Bachelor of Engineering (2003) and Master of Eng. (2007) at Ho Chi Minh city University of Technology and Education (HCMUTE), Mr Tam works at HCMUTE, as a lecturer, Faculty of Vehicle and Energy Engineering. Mr. Tam has been studying and researching about eclectric control system in automobile, as the focus in his PhD thesis.

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