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A Study on the Design and Application of Optimized Solenoid for Diesel Unit Injector

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With the Environmental Protection Agency (EPA) regulating the amount of NOx, Particulate, HC and CO at all driving conditions, emission standards for diesel engines are becoming more stringent than ever. To meet future emission regulations, researchers have proposed two solutions based on injection control, the common-rail type injection system, and the unit injection system. Most researchers agree that the electronically controlled unit injector, which realizes high injection pressure and precise control of SOI (Start Of Injection) and injection quantity, has an advantage in meeting future emission regulations. In order to control the start and end of injection, each unit injector contains a time-controlled high speed solenoid valve. Thus, the fuel injection quantity is determined by the time interval between closing and opening of the solenoid valve. This study introduces a method for the design of the solenoid which is installed in the unit injector. It is shown that there are certain significant parameters to be optimized to improve solenoid performance: inductance, stroke, input voltage, coil resistance, load and switching time.

Key Words : Unit Injector, Rising Time, Waiting Time, Optimal Inductance

Nomenclature

A : Projected area
B : Magnetic inductance
F_{mech} : Armature counterforce force
Fm : Traction force
H : Magnetic field strength
i : Current
i_w : Current when armature starts to move
I_y : Maximum current (U/R)
L : Inductance
L_0 : Initial inductance
R : Wire resistance
t_w : Waiting time
t_r : Rising time
U : Input voltage
ω : Wire number of turn
Θ : Magnetomotive force
Φ : Magnetic flux
Φ_w : Magnetic flux when armature starts to move
δ : Stroke
μ_0 : Permeability of vacuum

1. Introduction

To satisfy future emission regulations for diesel engines with respect to particulate and NOx levels, both the engine combustion system and the Fuel Injection Equipment (FIE) need to be improved (Shundoh, 1989, 1992, 1994). For the FIE, high injection pressure and variable injection timing as a function of engine speed, load, and intake temperature are very important parameters. Currently BOSCH is developing two different solutions :

1) An electronically controlled unit injector and single cylinder pump system ;

2) High pressure inline pumps with control sleeve and electronic control.

The new generation of electronic diesel fuel injection systems with special solenoid valves presents a complicated mechanical/electrical system. It involves a combination of mechanical

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motion, hydraulic pressure wave propagation, and the transient magnetic and electrical processes which interact with others. In this paper, the coupled dynamic behavior of the new system is studied based on a unit injector system developed at INHA university. A general physical model which can deal with other structure types such as the electronic pump-pipe-injector system and the distributor pump system is established. Traditional mathematical models for conventional mechanical injection systems or conventional solenoid valves are not suitable for the new type of injection system.

An attempt is made to develop a solenoid operated unit injector shown in (Fig. 1) for diesel engines and to inject fuel more exactly into the combustion chamber at high pressure(Kato, 1989; Shundoh, 1989b; Stumpp, 1989). These new injectors have the size of conventional diesel injectors with small but more powerful and ultra-fast solenoids (switching times of less than 3ms) located on the nozzle. To provide fast opening and closing time of the nozzle, a multi-objective optimization method is used to select the design variables of the injector. The mathematical model used for optimization is developed with the help of experimental results obtained from the solenoid force measurement at transient conditions. The optimization result did show good dynamic performance of the injector, despite the use of a small size solenoid actuator. The fast progress observed in recent years in the field of electronic fuel injection (such as Unit injector or Common-rail systems) with solenoid operated injectors for internal combustion engines, was mainly made in gasoline-driven spark-ignition engines. In developed engines, the hydraulic control of injectors by the high pressure fuel injection pump is still dominant. There have been attempts to introduce solenoid actuators to control the fuel injection process, but until now only a few such systems have veen available for commercial use. The reason is the requirement of very fast operation of diesel injectors to inject a closely controlled quantity of fuel during a very short time in hostile conditions of the engine combustion chamber(Wolber, 1984; Lauvin, 1991; Jurgen, 1995). When trying to inject gaseous fuels in the diesel engines, some researchers employed hydraulic control of injectors that requires the use of a conventional diesel fuel injection pump. A few years ago, an attempt was made at Concordia University to develop solenoid operated injectors for the direct injection of natural gas in diesel engines. Their results proved the feasibility of such a concept. The injector design was modified recently by introducing a small powerful solenoid into a commercially available diesel injector, in order to reduce its size and weight and to make it exchangeable with typical size injectors. In order to make its operation fast enough, a special switching circuit was developed and a multi-objective optimization method was applied to select the best design variables which can provide fast opening and closing of the injector.

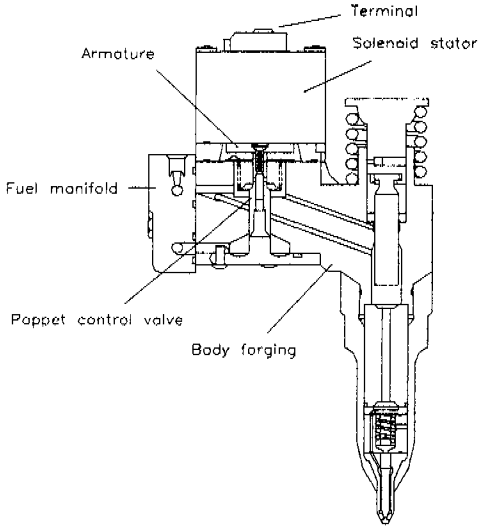

Fig. 1 BOSCH type Unit injector.

2. Solenoid Design

The response time consist of the waiting time and rising time; the waiting time is the time between the voltage occurring in wire and the start of armature moving, while the rising time is the time between the start and end of armature movement.

The input voltage is described as follows :

$$U=iR+\frac{d\phi}{dt} \tag{1}$$

where the magnetic flux is a function of current. The waiting time is as follows :

$$t_w=\int_0^{\Phi_w}\frac{d\Phi}{U-iR} \tag{2}$$

in which the current rises exponentially as

$$i=\frac{U}{R}(1-e^{-\frac{R}{L_0}t}) \tag{3}$$

So

$$t_w=\frac{L_0}{R}\ln\frac{I_y}{I_y-i_w} \tag{4}$$

where we can easily see that the solenoids parameters are current, displacement, magnetic flux, traction force, and inductance. These parameters are all functions of time.

2.1 Optimal inductance for switching time

This study suggests how to design the optimal solenoid which minimizes the response time for a given size. Inductance at given distance is defined as follows ;

$$L=\frac{\mu_0 A}{\delta}\omega^2 \tag{5}$$

The waiting time can be expressed as follows :

$$t_w=\frac{L_0}{R}\ln\frac{1}{1-\frac{R}{U}\sqrt{\frac{2F_{mech}\delta_0}{L_0}}} \tag{6}$$

if we defined d as ;

$$d=\frac{R}{U}\sqrt{2F_{mech}\delta_0}=\frac{\sqrt{2F_{mech}\delta_0}}{I_y} \tag{7}$$

then the optimal inductance for the waiting time is calculated as follows by differentiating Eq. (6)

$$L_{opt,w}=1.9533d^2=\frac{3.90665F_{mech}\delta_0}{I_y^2} \tag{8}$$

The optimal waiting time and optimal winding number are expressed as follows :

$$t_w=\frac{4.9F_{mech}\delta_0}{UI_y} \tag{9}$$

$$\omega_{opt,w}=\frac{2.79\delta_0}{I_y}\sqrt{\frac{F_{mech}}{\mu_0 A}} \tag{10}$$

Therefore we can easily determine the relationship between i_w and I_y at the optimal conditions. ($i_w=0.716I_y$) This equation shows that the optimal operating condition of rising current is approximately seventy percent of the maximum current at the given wire diameter. The general solution of the differential equation for the rising time takes into account all the main parameters of the solenoid

Eqs. (11) ~ (13) are used to calculate the rising time :

$$\frac{d\Phi}{dt}=\frac{U}{\omega}-i\frac{R}{\omega} \tag{11}$$

$$m\frac{d^2x}{dt^2}=k\Phi^2-F_{mech} \tag{12}$$

$$i=\frac{2k}{\omega}\Phi(\delta_0-x) \tag{13}$$

The initial conditions are as follows :

$$x=0\ ;\ \frac{dx}{dt}=0\ ;\ \Phi=\Phi_0=\sqrt{\frac{F_{mech}}{k}} \tag{14}$$

where

$$k=\frac{1}{2\mu_0 A} \tag{15}$$

and the inductance is

$$L=\frac{\omega^2}{2\delta\, k} \tag{16}$$

Therefore we obtain a rising time of

$$t_r=\sqrt[3]{\frac{3\delta_0 m}{U\sqrt{\frac{F_{mech}}{2\delta_0 L_0}}-R\frac{F_{mech}}{L_0}}} \tag{17}$$

We also get the optimal inductance for the rising time using the above equation

$$L_{opt,r}=\frac{8F_{mech}\delta_0}{I_y} \tag{18}$$

and

$$\omega_{opt,r}=\frac{2.83\delta_0}{I_y}\sqrt{\frac{F_{mech}}{\mu_0 A}} \tag{19}$$

The minimum rising time is therefore

$$t_{r,min}=\sqrt[3]{\frac{24\delta_0^2 m}{UI_y}}=\sqrt[3]{\frac{24R\delta_0^2 m}{U^2}} \tag{20}$$

2.2 Solenoid surge

If the solenoid is excited by current, the electrical energy changes to magnetic energy, and the magnetic energy is accumulated in the wire. At that time, if the current switches off, the accumulated magnetic energy can damage the wire. The surge voltage is approximately 120~360V which is roughly 10~30 times the input voltage (12V). Furthermore the bias voltage gives rise to a current in the neighboring wire via the conducting wire. If the chip which detects surge voltage from the input signal malfunctions, it becomes impossible to control the solenoid.

3. Experimental Method

3.1 Test bed

Figures 2 and 3 show the solenoid test bed and solenoid (rigidly attached to the test bed) for measuring the dynamic characteristics of the solenoid. The size of the solenoid is 28mm×20mm, the thickness of the silicon steel is 0.35mm, and the length of the core is 17mm. The projected area of the solenoid piled up againgt the silicon steel is 8 mm×20 mm. The bobbin is made of teflon for better operation at high temperatures. Part of the armature, spring support armature, and spring can be set force as desired. At the end of the armature, a lift sensor and permanent magnetic were installed to measure the lift of the solenoid. Data from the lift sensor can be read on the oscilloscope directly and stored. Nonmagnetic material is used for the solenoid supporter and sensor supporter. Pure iron is used for the armature in light of possible pile up problems. Solenoid stroke is adjusted by a dial gauge.

3.2 Circuit

In this study, the pulse width modulation method was used for controlling the current of the solenoid. Figure 4 shows the solenoid controller and stable 12 or 24voltage source which was used after filtering with two high-pass filters. To protect the solenoid from surge, a diode was connected in the positive direction, which decreased solenoid surge by 40%.

4. Experiment Results

4.1 Comparison of experimental data and simulation data for rising current and lift

Figure 5 shows experimental and simulation

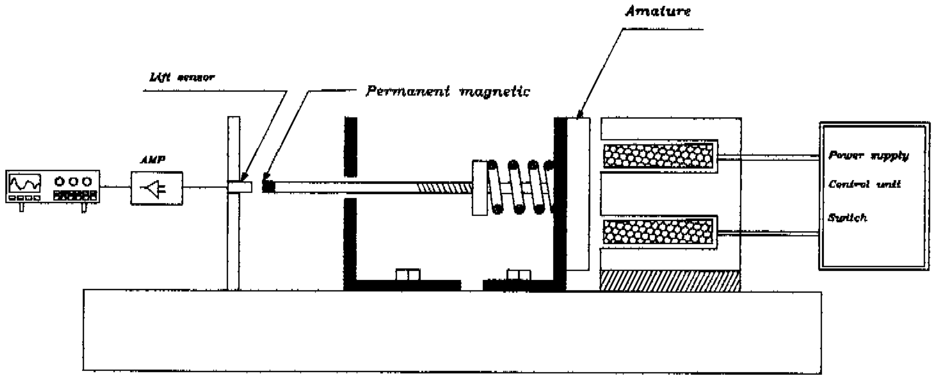

Fig. 2 Solenoid Test bed.

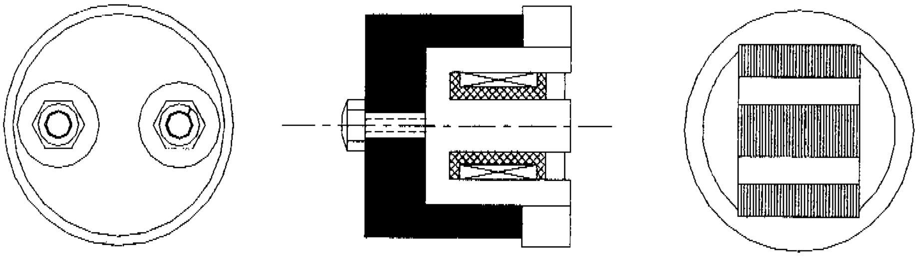

Fig. 3 Solenoid Structure.

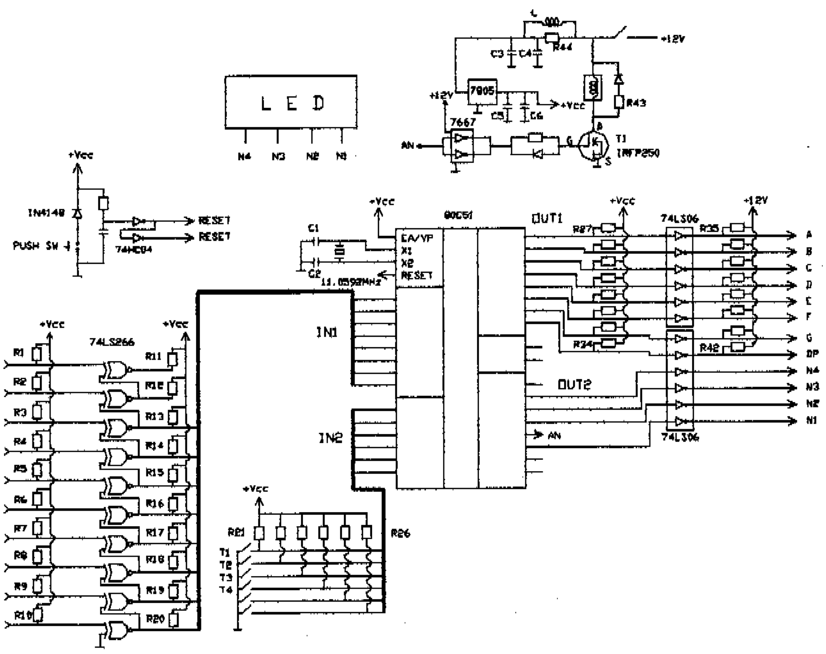

Fig. 4 Electric circuit diagram of Solenoid Controller.

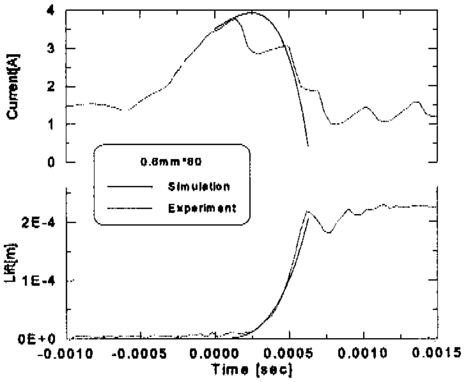

Fig. 5 Comparison of experimental data with simulation data.

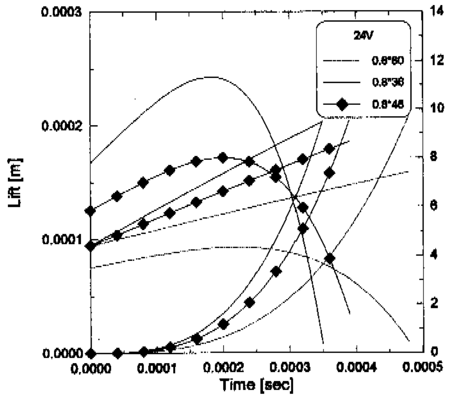

Fig. 6 Variations of current and lift according to the time.

results of the relationship between rising current and armature movement. Both results are relatively well matched when one neglects electrical noise. Also the data shows that there exists little difference in the armature movement at the last period between experiment and simulation. This result from the simulation neglects the mechanical force. The program considers the current saturation of the solenoid for precise simulation results. The reason for the current difference between simulation and experiment is that the program neglects the following nature of the system : all chips which were used in the circuit have a natural inner resistance, and PWM control was used as soon as the armature moves to reduce power consumption.

3.2 Relationship between stroke and rising current versus time

Figure 6 shows the stroke, current and magnetic flux according to wire diameter and winding number. In this figure, a high current implies fast movement of the armature, with fast operation of the solenoid implying higher power consumption for movement.

4.3 Stroke and traction force versus time

Figure 7 shows the stroke, current and traction force as a functions of time at 12V and 24V. This figure shows that applying 24V reduces the rising time by about 0.15ms compared with the 12V case. For the traction force, only the magnetic field was considered in the calculation. In real the situation, however, the inertia of the armature and spring force which vary according to position should be taken into consideration. The armature movement is described by

$$F=F_m+m\frac{d^2x}{dl^2}-k(\delta-x)$$

In the figure, the traction force at the armature starting point indicates 9kgf a preloaded force of Power consumption can be calculated easily by integration of the square current times resistance. As the armature nearly reaches the core, the traction force decreases to below the preloaded. This phenomenon is caused by reduction of the current due to rising inductance, but in spite of reduced current, the armature continues to move under the influence of inertia forces.

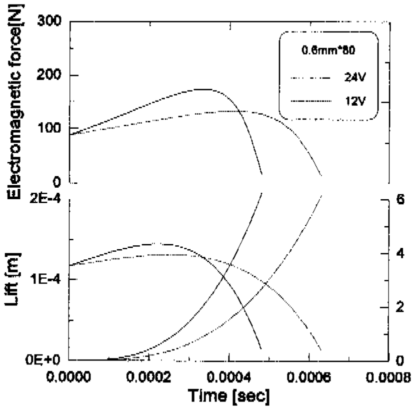

Fig. 7 Variations of stroke and traction force with time.

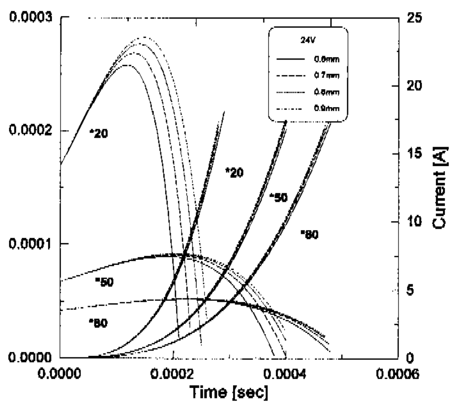

Fig. 8 Dynamic characteristics of solenoid.

4.4 Switching time of the solenoid with different wire diameter and winding number

Figure 8 shows the stroke, current and switching time with different the wire diameters and winding numbers. In this figure, the wire diameter has little effect on the current and switching time of the solenoid. however, the winding number does affect the switching time, as well as the size of the solenoid for the same wire diameter. If we ignore other factors, this relation is of great significance in the design of the solenoid.

4.5 Solenoid efficiency and instant acceleration

Figure 9 shows the efficiency and instant acceleration with repect to switching time. This figure can be used to determine the optimum solenoid for each case. All the electical energy cannot be converted to kinetic energy of the solenoid when the electrical field excites the magnetic field. Here the efficiency of the solenoid is defined as fol-

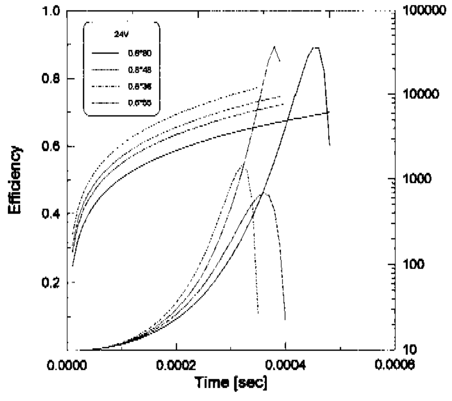

Fig. 9 Variations of solenoid acceleration and efficiency with time.

lows :

$$\eta=\frac{\mathrm{m(mass)}\cdot\mathrm{a(instant\ acceleration)}\cdot\mathrm{x(stroke)}}{\mathrm{V(voltage)}\cdot\mathrm{I(current)}\cdot\mathrm{t(time)}}$$

Both 0.8mm×48 and 0.6mm×80 cases show good efficiency ; comparing the efficiency of the two, the former is the better if we consider switching time. In the real case, 0.8mm×48type solenoid shows higher current than simulation results due to current saturation. Therefore, desspite slow switching time, we can conclude that 0.6mm×80type solenoid in which current saturation does not occur has better solenoid efficiency.

5. Conclusion

The results of the paper can be summurized as follows :

1) The simulated results are well matched with the experimental results if PWM control is neglected.

2) The rising time increases according to an increase winding number at the same wire diameter, while the rising current decreases according to an increase in inductance.

3) The waiting time and rising current increases according to preloaded force, the increasing but rising time decreases in this case.

4) Generally, a fast solenoid means high rising current and high power for operation.

5) Response time is affected more by the winding number of the wire rather than wire diameter.

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