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Diesel Engine Fuel Injection Control with DDVC Hydraulic System

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Abstract: Internal-combustion engine has been used on ship, automobile and so on. However increase of internal-co mbustion engine caused to the environmental and energy problem in those days. Then we must improve the perform ance of it from the level of combustion. From this point of view, we put the target on a diesel engine which is us ually used on ship as the main propulsion engine. Its performance is depending on a fuel injection system and it is well known that controlling injection optimally reduce the fuel consumption and amount of toxic substance. In this study, we proposed a new fuel injection system using Direct Drive Volume Control (DDVC) hydraulic system, and d eveloped basic control method for fuel injection. The new fuel injection system is constructed with conventional inje ction valve and new fuel pump using DDVC hydraulic system. We have already established the method to control f uel injection timing, duration, pressure, rate and pattern.

Keywords: Environmental and energy problem, Fuel injection system, DDVC hydraulic system.

1 INTRODUCTION

In these days, electric fuel injection system is used to improve the combustion efficiency and reduce amount of toxic substance for diesel engine. Common rail type electric fuel injection system is one of the most popular for it. It is keeping high-pressure oil in common duct and inject it into the cylinder with the on-off of electro-magnetic valve equipped on the fuel injection valve. However, it is expensive because it should use high cost material for high pressure common duct and specialized injection valve.

Another electric fuel injection system is also expensive with use of complex pressurizing system and specialized injection valve. Taking into account those situations, we proposed new electric fuel injection system which is constructed with DDVC hydraulic System and using conventional (mechanical) fuel injection valve.

In the conventional electric fuel injection system, effective fuel injection method for improving combustion efficiency and reduction of toxic substance is established.

Here we confirmed that the new injection system is available to realize effective fuel injection with control of DDVC hydraulic system.

2 DDVC TYPE FUEL INJECTION SYSTEM

DDVC type fuel injection system is including DDVC actuator, booster unit and fuel injection valve. System configuration is shown in **Fig. 1.**

DDVC actuator is constructed with AC servo-motor driven reversible gear pump and hydraulic cylinder called low-pressure cylinder. The motion of cylinder piston is controlled with revolution of servo-motor and we can get the high pressure which is proportional to the ratio of cross-section of both cylinders when it pushes the piston of spring back type booster cylinder.

This high pressure fuel is send to injection valve and injection will start when the pressure overcome than spring force in the valve. The fuel injection valve is cheaper and low failure rate because it is not special type.

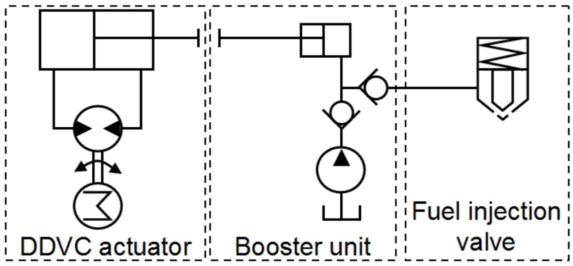

Fig. 1. DDVC type fuel injection system

3 MATHEMATICAL MODEL OF DDVC FUE L INJECTION SYSTEM

3.1 Mathematical model of the DDVC actuator

As shown in **Fig.1 .**, discharged oil from gear pump is supplied to cylinder and pushes piston, and the oil in another side of cylinder is lead to pump suction.

When the piston can move freely, the motion of piston is written with following equation.

$$m_1 \ddot{x}_1 + c\dot{x}_1 + kx_1 = p_1 A_1 \tag{1}$$

Here, m_1 is the mass of piston, c is friction coefficient, k is spring constant, p_1 is the pressure of head piston A_1 is cross sectional space cylinder, and x_1 is displacement of piston.

When the piston is attached to the booster, both piston moves together and kinematic equation become as follows.

$$(m_1 + m_3)\ddot{x}_1 + c\dot{x}_1 + kx_1 = p_1 A_1 - p_2 A_2 - p_3 A_3 \quad (2)$$

Here, m_3 is the mass of booster piston, p_2 is the pressure of booster piston, p_3 is the pressure of booster, A_2 is cross sectional of booster piston, A_3 is cross sectional of booster.

3.2 Mathematical model of booster

If the fuel injection does not start, change rate of high-pressure pipe oil pressure shown in the Eq.(3)

$$\dot{p}_3 = \left(k/\left(V_4 - A_3 x_3\right)\right)A_3\dot{x}_3 \quad (3)$$

Here, V_4 is the volume of booster unit, x_3 is displacement of booster piston.

$$V_4 - A_3 x_3 \approx V_3 \quad (4)$$

After two pistons are contacting,

$$x_3 = x_1 \quad (5)$$

Therefore, change rate of oil pressure in booster is Eq.(6)

$$\dot{p}_3 = (k/V_3)A_3\dot{x}_1 \quad (6)$$

With integrating Eq.(6), we can get oil pressure in the booster

$$p_3 = (k/V_3)A_3 x_1 + p_{31} \quad (7)$$

After injection started, oil pressure in the booster is written with following equation.

$$\dot{p}_3 = (k/V_3)\left(A_3\dot{x}_1 - a\sqrt{2p_3/\rho}\right) \quad (8)$$

And oil pressure in the booster becomes as follows.

$$p_3 = k/V_3\left(A_3 x_1 - \int Q_i dt\right) + p_{32} \quad (9)$$

When fuel injection is continuing, the change rate of oil pressure will become as Eq.(10)

$$\dot{p}_3 = (k/V_3)\left(-a\sqrt{2p_3/\rho}\right) \quad (10)$$

Then, the oil pressure in the booster is Eq.(11)

$$p_3 = -k/V_3 \int a\sqrt{2p_3/\rho}\,dt + p_{33} \quad (11)$$

3.3 Mathematical model of a fuel injection valve

Fuel injection valve is very important part in fuel injection system. When fuel pressure overcome to spring force, the needle is lifted up and injection starts. Here we make a mathematical model for injection valve as the relation between fuel pressure, motion of needle and flow rate of injection. Unfortunately the flow rate should be estimate because it is difficult to measure. The model of fuel injection valve are illustrated in **Fig. 2.**

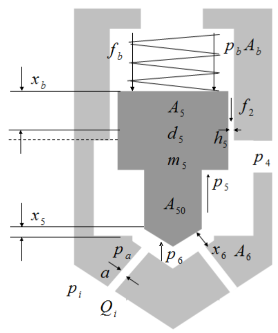

Fig. 2. Fuel injection valve

Kinematic equation of needle valve is shown in Eq.(12)

$$m_5\ddot{x}_5 = p_6(A_5 - A_{50}) + p_6 A_{50} - p_b A_b + f_b + f_2 \quad (12)$$

Here, f_b , f_2 shows spring force, damping force respectively. Those are shown as following equations.

$$f_b = -k_b x_5 \quad (13)$$

$$f_2 = -\mu\pi d_5(x_b + x_5)\dot{x}_5/h_5 \quad (14)$$

We assume there exist no time delay on a pressure of fuel. Then,the injection valve has four (4) injection nozzles.

$$p_3 + \frac{\rho}{2}\left(\frac{Q}{A_6}\right)^2 = 4\left(p_a + \frac{\rho}{2}\left(\frac{Q}{a}\right)^2\right) \quad (15)$$

In accordance with it,

$$Q = \frac{a}{4}\frac{1}{\sqrt{1-(a/4A_6)^2}}\sqrt{\frac{2(p_3 - 4p_a)}{\rho}} \quad (16)$$

When the fuel is injected to air, the flow rate will be Eq.(18)

$$Q_i = \frac{a}{4} \frac{1}{\sqrt{1-(a/4A_4)^2}} \sqrt{\frac{2p_3}{\rho}} \tag{17}$$

As

$$a/4A_4 \approx 0, \tag{18}$$

The flow rate becomes as follows finally.

$$Q_i = \frac{a}{2}\sqrt{\frac{p_3}{\rho}} \tag{19}$$

4. INJECTION CONTROL

4.1 Fuel pressure at booster

Oil pressure at the outlet of booster is determined with displacement and speed of piston, and injection flow rate at fuel injection valve. Since fuel injection valve is mechanical self balance type, we control fuel pressure not at injection valve but booster with displacement and speed of high-pressure cylinder piston.

In DDVC hydraulic actuator, input voltage to the driver of servo-motor has proportional characteristics to the piston speed of low-pressure cylinder. Then we use input voltage for basic estimation of piston speed and add the difference of actual position and estimated position to correct the value. The result of estimation is shown in **Fig. 3.**

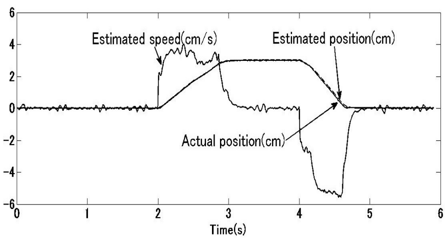

Fig. 3. Piston speed of low-pressure cylinder

In booster unit, volume change of high pressure line with the displacement of high-pressure cylinder is much smaller to total volume of high-pressure pipe.

With this reason, we ignored the influence of high-pressure cylinder piston displacement to the pressure in our experiment and to examine the relationship of low-pressure cylinder piston speed and oil pressure of high-pressure pipe, .we checked the fuel pressure when the input voltage is-2v,-4v,-8v.

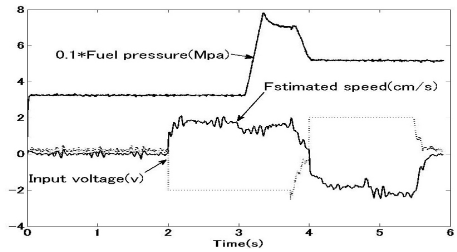

Fig. 4. Results at -2V of input voltage

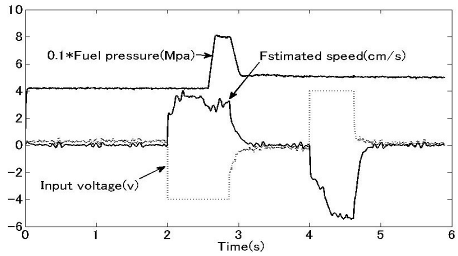

Fig. 5. Results at -4V of input voltage

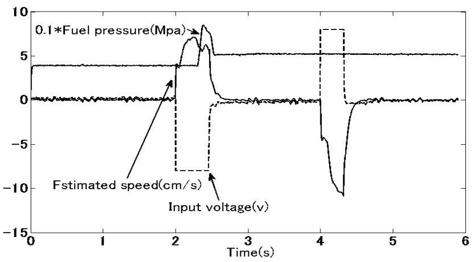

Fig. 6. Results at -8V of input voltage

Those results show that the fuel pressure is rising with the piston speed from contact of both pistons to start of injection. After fuel injection start, the fuel pressure decrease because initial flow rate of injection is so large that piston speed cannot follow to it. However piston speed is rising and it can follow to injection and fuel pressure increase again.

This shows that fuel pressure can be controlled with the speed of low-pressure cylinder.

Control method and control results of fuel-pressure is shown in **Fig. 7.** and **Fig. 8.**

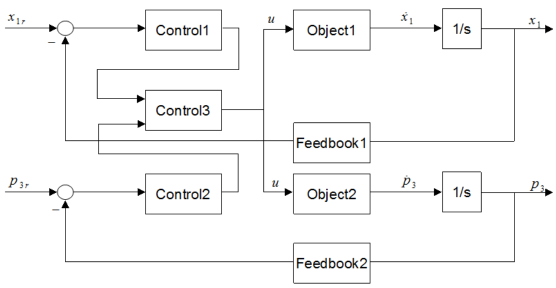

Fig. 7. Control method of fuel pressure

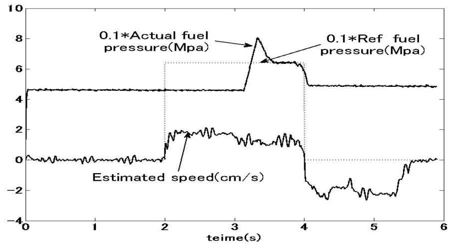

Fig. 8. Control results of fuel pressure

4.2 Fuel injection flow and rate

If initial fuel pressure is same as the pressure of after injection, we can think that the quantity of injected fuel is equal to compressed volume. Considering this, we examined the relationship between injected quantity, piston displacement of low-pressure cylinder and fuel pressure. It is shown in **Fig. 9.**

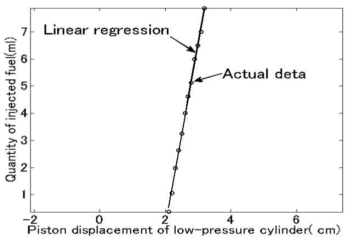

Fig. 9. Relationship between quantity of injected fuel and piston displacement of low-pressure cylinder

Actual flow of fuel injection and estimated flow, estimated rate are shown in **Fig. 10.**

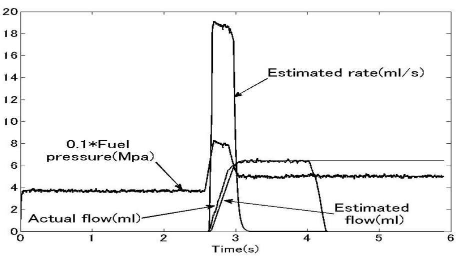

Fig. 10. Actual flow and estimated flow, rate of fuel injection

This result shows that for precise control of fuel injection, piston displacement of low-pressure cylinder should be controlled more precisely.

When conventional P-control is applied for the piston displacement control, offset will remain and when we add I-control for it, it becomes cause to overshoot .Here, we propose a new method to protect offset and overshoot effectively. This method is shown in **Fig. 11.**Control result for piston displacement of Low-pressure cylinder and fuel injection flow with this method is shown in **Fig. 12.** & **Fig. 13.**

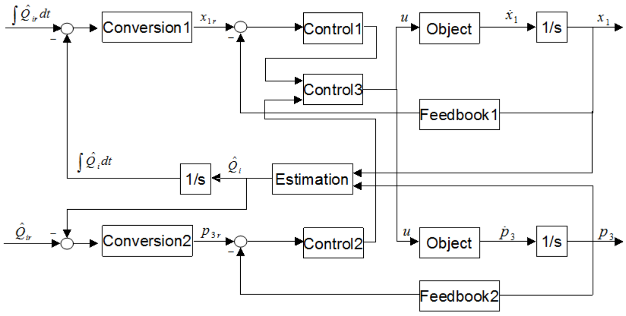

Fig. 11. Control method of injection flow and rate

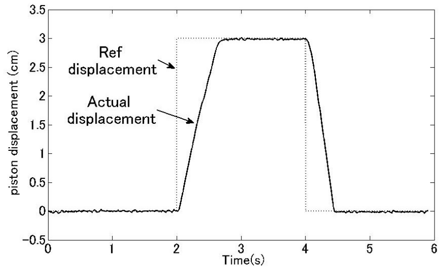

Fig. 12. Control result of piston displacement

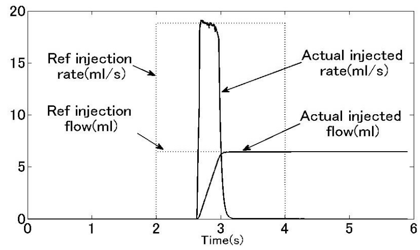

Fig. 13. Control result of injection flow and rate

5 CONCLUSION

In this research, we have constructed the control method of diesel engine fuel injection with DDVC hydraulic system. We can control fuel pressure with the motion of piston in low pressure cylinder, and injected fuel quantity, injection timing or injection rate with using simulation.

Now we are expanding it to total system including the combustion in cylinder and confirming the reduction of fuel consumption, particle emission, and toxic substance such as oxide frugal gas with control to the new fuel injection system.

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