伺服閥控制射出成型機之射出速度自動調整伺服控制器研究
The AutoTuning Servo Controller of Injection Speed for the Servovalve Controlled Injection Molding Machine

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摘要
本文主要係探討射出速度自動調整伺服控制器在伺服閥控制射出成型機之實際應用，此技術可大量減少使用不同模具及塑膠材料時之人工調整工作。射出速度自動調整伺服控制器的主要目的係使射出成型機射出單元的螺桿速度可由電液伺服閥配合閉迴路控制之自動調整技術執行控制。由模擬結果知，本文所發展之自動調整伺服控制器可吻合實際實驗性能，而實驗結果更顯示此控制器性能優於傳統 PID 控制器。
關鍵詞：射出速度，伺服閥，自動調整伺服控制器

Abstract
This paper is about the practical application of the autotuning servo controller of injection speed for the servovalve controlled injection molding machine. The manual tuning work for the various resin and mold can be mostly reduced by this technique. The purpose of this controller is that the injection speed of the injection unit in the injection molding machine can be controlled by a servovalve in the molding process by the autotuning closed loop control theory. The simulation results show this controller predition adequately agrees with the experimental data and the experimental results also have shown the autotuning servo controller is superior to the convensional PID controller.
Keywords: injection speed, servovalve, AutoTuning Servo Controller

I. INTRODUCTION

In the injection molding process, Chiu and Hsieh [1] have been shown the injection stage is the most important stage affecting the level of residual stresses developed in molding ABS. When the molten polymer is injected into a mold, the injection speed may be kept at a constant value in the injection stage to get a high quality product, This is because it affects the molecular orientation and the skin formation of the parts. The most widely used in the injection speed control are the ram speed, the hydraulic pressure and the cavity pressure control [2]. For example, Thayer and Davis [3] first used a servovalve to perform the feedback control of the ram speed in an injection molding machine. Costin, and others[4] applied the model of hydraulic pressure to design the self-tuning regulator to preserve a constant hydraulic pressure gradient during the injection satge. Chiu, and others[5] applied the adaptive model following controller to the cavity pressure control in a servovalve controlled injection molding machine.

The injection speed control of the conventional machine is controlled by setting the relief valve and the manual orifice valve. This open loop control is susceptible to the nonlinearities of parts because of the oil temperature change, wear and friction of the machine, the valve and other uncertainties. The practical answer to solve these problems is the closed loop control which can improve the repeatability and resetability of the injection molding process[6]. The closed loop controller mostly used in the injection molding machine is the PID controller. However, the PID controller did not satisfy the process control because of the nonlinear relations of the flow and pressure characteristics of the hydraulic system or because of the flow characteristics of the polymer. Therefore, the design of the autotuning servo controller is important for tuning these PID parameters.

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In this paper, we focus on the practical application of the autotuning servo controller of injection speed for the servovalve controlled injection molding machine. The purpose of the autotuning servo controller is the injection speed of the injection unit in the injection molding machine can be controlled by a servovalve in the molding process by the autotuning closed loop control theory. The manual tuning work for the various resin and mold also can be mostly reduced by this technique. The control system resulting from this approach will force the autotuning servo controller of injection speed to be a highly nonlinear controller, which can be represented by a set of nonlinear ordinary differential equations. These equations are solved by the software of Matlab & Simulink to show the performance of this controller. The results show this controller prediction adequately agrees with the experimental data. The experimental results also have shown the autotuning servo ccontroller is superior to the convensional PID controller.

II. THE AUTOTUNING SERVO CONTROLLER OF INJECTION SPEED

A nonlinear model of the autotuning servo controller of injection speed using a servovalve as the control element in the injection molding machine will be developed. A schematic diagram of the control system is given in Figure 1. The error signal *e(t)* of the injection speed can be calculated as follows:

$$e(t) = V_c - \frac{dx}{dt} \quad (1)$$

where V_c is the injection speed command and $\frac{dx}{dt}$ is the injection speed.

This injection speed controller mostly used in the injection molding machine is the PID controller, its output m*(t)* gives:

$$m(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \quad (2)$$

where K_p is the proportionate gain, K_i is the integration gainand K_d is the derivative gain.

This injection speed controller is designed as a single-chip 16-bit digital controller. In this control system, the machine controller gives the injection speed command to the injection speed controller. The injection speed controller accepts this command to calculate the properly control signal by Eq.(2), and then output the signal to the servovalve by the D/A converter to achieve the closed loop control.

The screw type injection molding machine used in this study is made by Chin-U Co. Ltd.(Model No. TMC—90E) and the hydraulic oil flow in the injection cylinder is controlled by a four-way electrohydraulic servovalve (MOOG J661-562). Figure 2 shows the MOOG servovalve

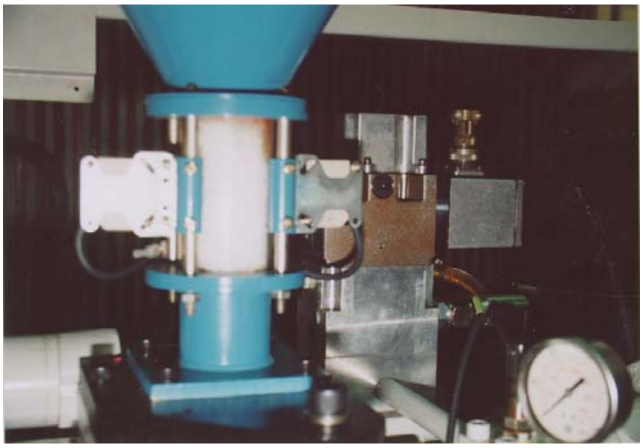

Fig. 2 MOOG servovalve on the injection unit of the TMC machine

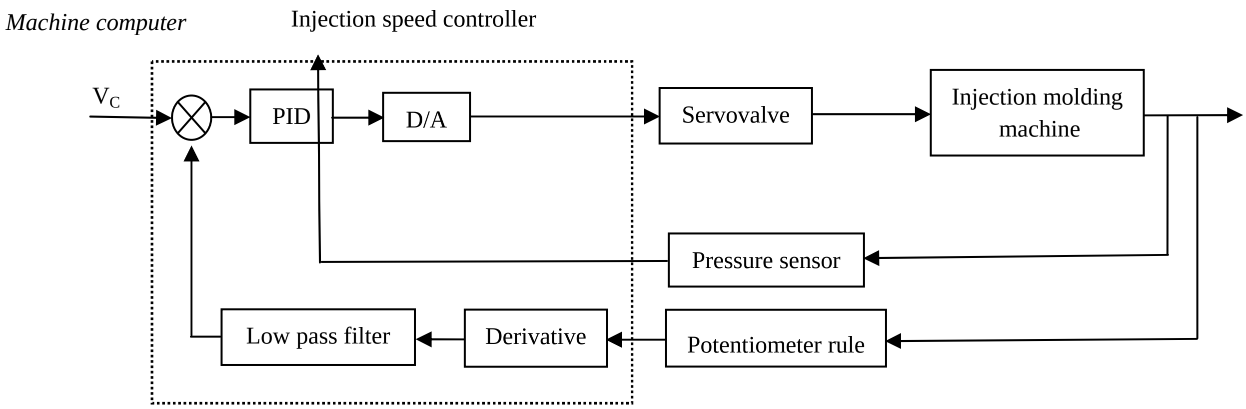

Fig. 1 A schematic diagram of the autotuning servo control system

is built on the injection unit of the TMC machine. The ervovalve is chosen as a three-way type and gives a larger flow rate. Its static and dynamic characteristics are given in the following equations [2]：

$$\frac{dx_v}{dt}=\frac{1}{\tau}[-X_v+K_v m(t)] \tag{3}$$

where X_v is the spool position, K_v is the servovalve constant and τ is the time constant of the servovalve.

$$\begin{aligned} Q&=K_g X_v\sqrt{P_s-P} && for \quad x_v>0 \\ Q&=K_g X_v\sqrt{P} && for \quad x_v<0 \end{aligned} \tag{4}$$

where Q is the servovalve control flow, K_g is the servovalve flow gain, P_s is the supply pressure and P is the injection pressure.

Eq.(3) explains the dynamic relationship between the spool position and the control input voltage, Eq.(4) describes the static flow characteristics of the servovalve. The constants such as K_v, K_g….are calculated from the MOOG servovalve model J661-562 which are listed in the Table 1 of ref. [7].

The hydraulic system is controlled by an injection speed controller and is designed using a pump with an accumulator to achieve the 200 mm a sec max. injection speed. The response of supply pressure can be estimated using a first order differential equation model which is given by [2] :

$$\frac{dP_S}{dt}=\frac{1}{\tau_1}(-P_S+P_{SC}) \tag{5}$$

where P_{SC} is the supply pressure command and τ_1 is the time constant of hydraulic system which depends on the hydraulic piping system design and the running condition of the injection molding machine.It will be estimated from the experimental data.

In the injection cylinder, the continuity equation of the hydraulic oil flow shows:

$$\frac{dP}{dt}=\frac{\beta}{V_0+Ax}(Q-A\frac{dx}{dt}-Q_L) \tag{6}$$

where V_0 is the volume of oil in the injection cylinder when x=0, A is the cross-sectional area of the injection cylinder, β is the bulk modulus of hydraulic oil and Q_L is the leakage flow of oil. Eq.(6) is a nonlinear differential equation because of the screw position x in the denominator. Application of the force balance equation on the actuator-screw assembly gives:

$$M\cdot\frac{d^2x}{dt^2}=P\cdot A-B_f\frac{dx}{dt}-F_c-F_d \tag{7}$$

where M is the mass of actuator-screw assembly, B_f is the viscous damping coefficient, F_C is the coulombic friction force and F_d is the total pressure at the barrel product to the screw cross area. The values of F_c and F_d are difficult to get and must be estimated from the experimental data [7], so the Eq.(7) is a nonlinear differential equation. The machine parameters in the Eq.(5) to Eq.(7) are listed in Table 1 of ref. [7].

This autotuning servo controller is developed in this paper which uses the hydraulic pressure signal to compensate for the injection speed, and the PID parameters are tuned as follows：

$$KPID(t)=KPID(0)+\Delta K_{PID}(t) \tag{8}$$

KPID(t) in the equation represents the time function of three PID parameters which have two parts, that is, initial values *KPID(0)* and variations $\triangle K_{PID}(t)$. *KPID(0)* are chosen as the three PID parameters of the convensional PID controller, and the variation $\triangle K_{PID}(t)$ is developed by the disturbance effects of the injection molding process. Thus, $\triangle K_{PID}(t)$ in Eq.(8) can be assumed as a linear function of the hydraulic pressure on the injection molding process, which are shown as follows:

$$KPID(t)=KPID(0)[1+K_L\cdot P] \tag{9}$$

where P is the injection pressure at the injection cylinder and is a time-varying function. The value of K_L in the equation is the adaptive gain of the servo controller, and it controls the adaptive rate of *KPID(t)*. Eq.(9) explains the hydraulic pressure signal is used to compensate for this controller, thus the on line three PID gains *KPID(t)* are tuned. When this signal is not used (P=0), the injection speed controller is the convensional PID controller. Eq.(9) also showed the adaptive gain K_L is set to zero, this controller is also the convensional PID controller. Therefore, the design procesures of this controller can be shown as the following steps:

1. The conventional PID controller design, that is, searching the initial values $K_{PID}(0)$ and must ensure the injection speed control system is stable.

2. The experimental test of the conventional PID controller on the injection molding machine to ensure Step (1) is acceptable.

3. The choice of adaptive gain K_L to produce a correction signal which is superimposed on the conventional PID signal to ensure the performance of the plant is stable.

4. The experimental test of the pressure compensated injection speed controller on the injection molding machine to ensure the compensated effect is acceptable.

Figure 3 shows a Matlab & Simulink simulation program of this autotuning servo controller of injection speed on the servovalve controlled injection molding machine. This diagram is used for the simulation and designing this nonlinear controller.

III. EXPEMENTAL APPARATUSES AND PROCEDURES

The expemental apparatuses and procedures are listed as follows:

Measurement terms: screw position, hydraulic pressure and servovalve opening.

Sensors: hydraulic pressure sensor and screw position potentiometer.

Measurement system: IO－TECH data acquisition system and notebook.

Mold: fly disk shape mold.

Resin: PP.

Measurement procedures :

1. The max. injection speed condition tests of the autotuning servo controller to ensure the compesated effect is acceptable.
2. The performance tests of the autotuning servo controller of injection speed under the choice of adaptive gain K_L to ensure the performance of the controller.

IV. RESULTS AND DISCUSSION

Figure 4 shows a comparison of the simulation results of the injection speed responses at 90% max. speed. In this case, the initial values of *KP (0)*=0.015, *KI (0)*=3.0, and the adaptive gain K_L =2.0. From this figure, the autotuning servo controller of injection speed ensure that the compesated effect is acceptable.

The experimental results of the autotuning servo controller and PI control of the injection speed responses at

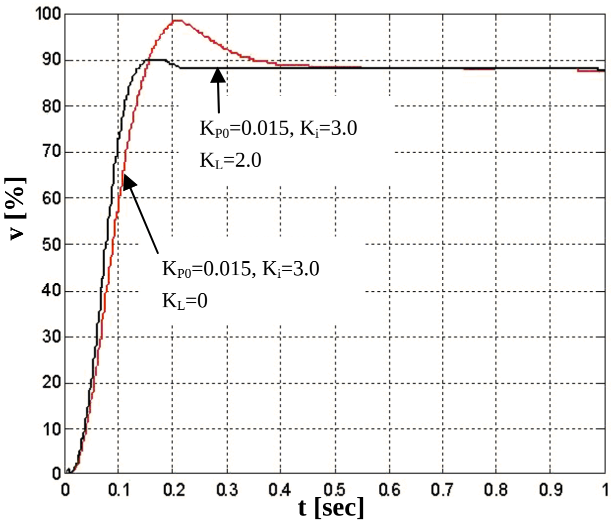

Fig. 4 The simulation results of the injection speed responses at 90% max. speed

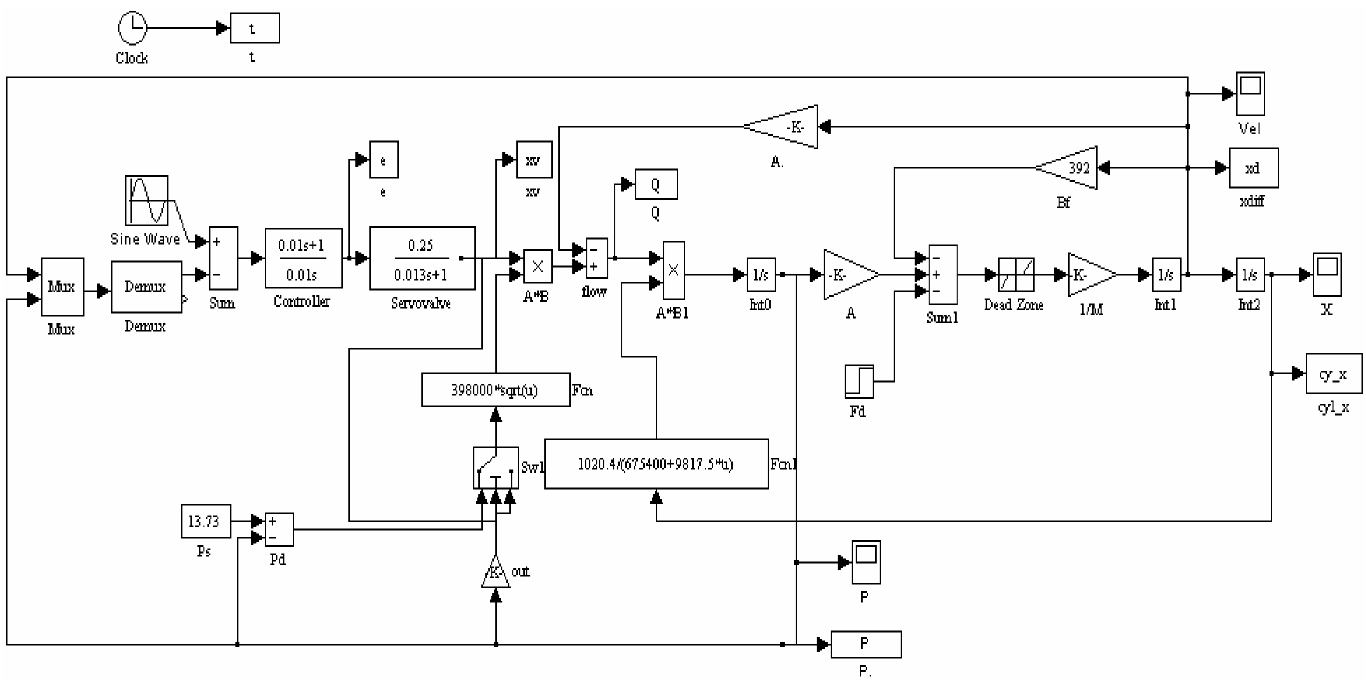

Fig. 3 The simulation program for the injection speed controller

90% max. speed are shown in Figure 5. The results show the servovalve opening is increasing with the hydraulic pressure for the case of autotuning, but the PI control does not have this effect. In this moment, the injection speed control effect has a large improvement. In this case, step 3 of the design procedure is established.

Figure 6 shows the experimental results of the injection speed with different K_L at 25% max. speed. In the upper diagram, the tracking performance of the pressure compensated (K_L=10) case is much better than the nontuned (K_L=0) case. In the lower diagram, the on-line tuning process of *KP (t)* can be shown. Its values are changed from 0.005 to 0.023 in the tuned case (K_L=10). In the nontuned (K_L=0) case, the values of *KP (t)* are always constant (=0.005) during the injection process. Therefore, the K_L parameter depends on the kinds of resin and mold shapes and controlling the adaptation rate of *KP* (t). that is, the adaptation rate of *KP* (t) is proportional to the K_L. When the K_L is a constant, the adaptation rate of *KP* (t) or the slope of *KP* (t) is proportional to the injection speed.

The injection speed responses with different adaptive gain K_L at 99% max. speed are shown in Figure 7. In the upper diagram, the tracking performance of the tuned case (K_L=10,20) are also much better than the nontuned (K_L=0) case. In the lower diagram, the K_L parameter increases from 10 to 20, the injection speed can't increase because of the saturation effect of the actuation system.

Figure 8 shows the experimental results of the injection speed with different adaptive gain K_L at the command from 25% to 75% max. speed. In the upper diagram, the tracking performances of the tuned case (K_L=10) are much better than the other case (K_L=0,5) at 25% and 75% max. speed. In the lower diagram, we can find the better K_L parameter is 10.

From the simulated and experimental results, this controller has the following special characteristics:

1. The adaptive gain K_L is introduced to gain the tuning rate of PID parameters, and the on-line tuning rate of *KPID(t)* also depends on the various resin and mold shape.

2. The tuning mechanism produces a correction signal which is superimposed on the conventional PID signal to ensure the tuning performance. When the correction signal is null, the control loop is the conventional PID control loop.

3. The autotuning servo controller is superior to the conventional PID controller.

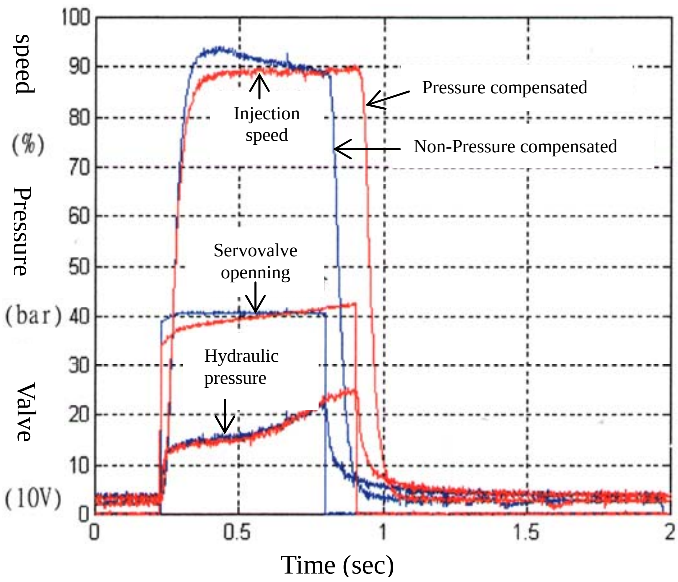

Fig. 5 The experimental results of the injection speed responses at 90% max. speed

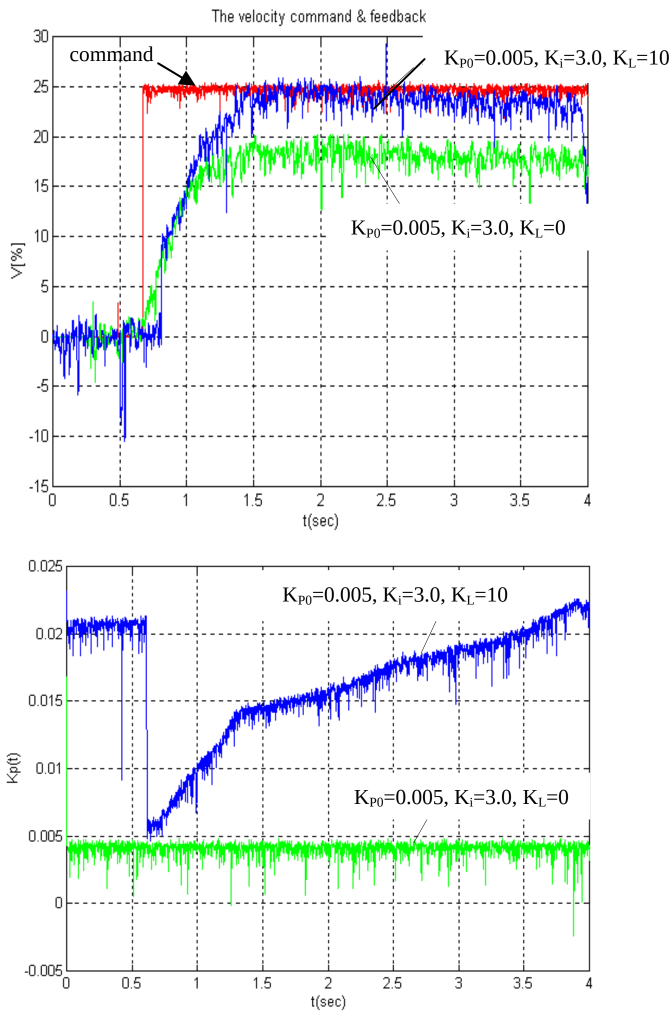

Fig. 6 The experimental results of the injection speed with different K_L at 25% max. speed

V. CONCLUSION

The simulation and experimental results have pointed out autotuning based on the PID controller is potentially useful for the injection speed control on the servovalve controlled injection molding machine. The manual tuning work for the various resin and mold can be mostly reduced by this technique. The results also have shown the auto-tuning servo ccontroller is superior to the convensional PID controller.

The variations $\triangle K_{PID}(t)$ in Eq.(8) can be assumed as a linear function of the hydraulic pressure on the injection molding process. Therefore, the hydraulic pressure at the injection cylinder has a compensated effect on the servo system of injection speed.

The value of K_L in the equation (9) is the adaptive gain of the servo controller, and it controls the adaptive rate of *KPID(t)*, thus the on line three PID gains *KPID(t)* are tuned. When this hydraulic pressure signal is not used (*P*=0), the injection speed controller is the convensional PID controller. Eq.(9) also showed the adaptive gain K_L is set to zero, this controller is also the convensional PID controller.

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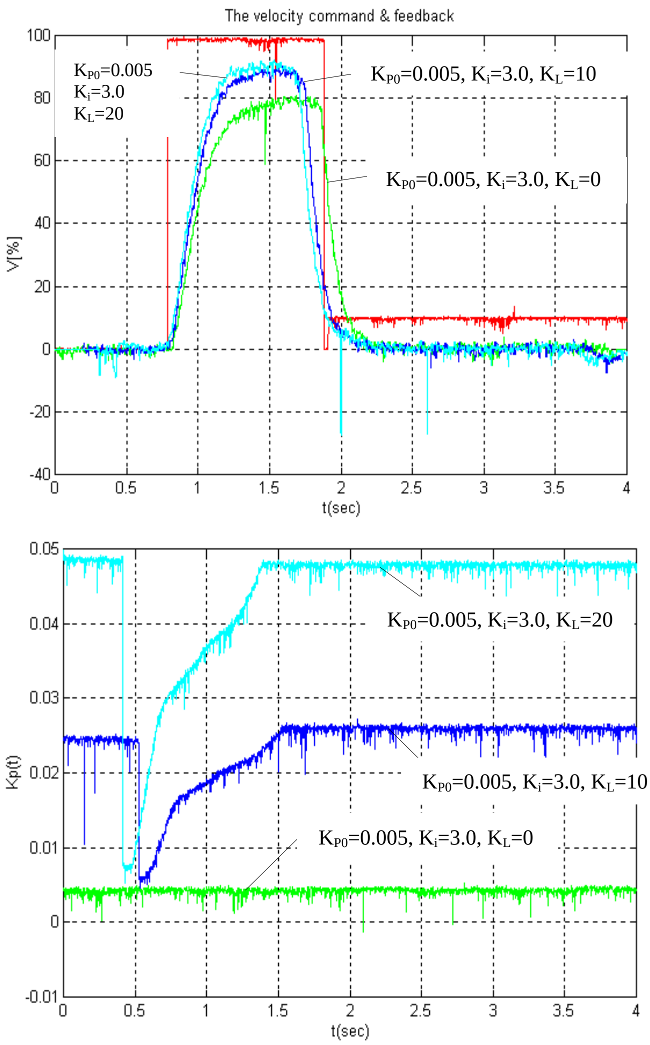

Fig. 7 The experimental results of the injection speed with different K_L at 99% max. speed

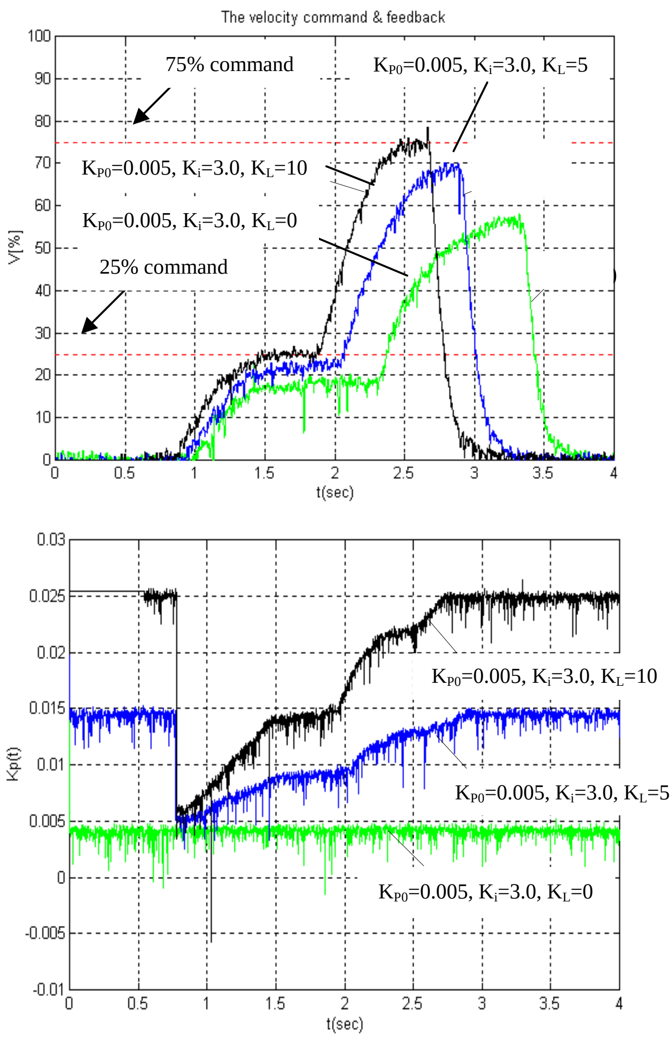

Fig. 8 The experimental results of the injection speed with different K_L at the command from 25% to 75% max. speed

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