Proceedings of the American Control Conference
Chicago, Illinois • June 2000

Learning Control of an Electro-hydraulic Injection Molding Machine with Smoothed Fill-to-Pack Transition[1]

Danian Zheng Andrew Alleyne
Dept. of Mechanical and Industrial Engineering
University of Illinois, Urbana-Champaign
1206 West Green Street
Urbana, IL 61801

ABSTRACT:

In this paper a learning control scheme with a bumpless transfer between the filling phase and packing phase is designed and tested on an experimental Injection Molding Machine (IMM). Building upon the learning scheme tested in Havlicsek and Alleyne (1999b), the current control system takes into account both of the two learning control phases and initiates a smooth transition between them. A high gain bumpless transfer scheme is described and tested successfully. The experimental results presented show much better performance for the transition between the two learning controllers. Under the current scheme, when the second (packing phase) controller takes over, the IMM system has a significantly smoother control signal and pressure transient than the scheme presented in Havlicsek and Alleyne, (1999b). The current scheme partially resolves the problem of the fill-to-pack transition in IMM control.

1. INTRODUCTION:

In modern Injection Molding Machines, electro-hydraulic systems are commonly used as actuation mechanisms for directing the melted polymer material into a mold thereby forming plastic parts with a desired shape. The entire process can be separated into several phases. Two key phases to be considered in this work are the filling phase and the packing phase of the cycle. During the cycle, adequate injection speed and pressure profiles are required to guarantee the proper microstructure and density of the parts produced. Although electrohydraulic systems are very common in IMMs, particularly for heavy load applications and larger parts, they do possess nonlinear characteristics that their electromechanical counterparts may not. Therefore the problem is more challenging for control engineers.

There have been several methods developed and implemented for injection molding control. They range from basic sequential open-loop control, to more sophisticated closed-loop feedback control, and adaptive control based on sensing of machine movement and cavity pressure. Closed-loop controllers were initially developed (Thayer & Davis, 1980) to deal with the non-linearity and the unmodeled dynamics of the machines and provided significant gains over open-loop approaches. Recently, a fuzzy logic controller was implemented to tune the controller to adapt for changing machine parameters (Tsoi & Gao, 1998). In the same vein, an adaptive self-tuning controller (Gao et al, 1996) was reported which also performed online tuning of the controller parameters for better performance. However, neither of the aforementioned approaches specifically addresses the transition between the fill phase control and the pack phase control nor do they suggest methods to minimize the transients associated with the changeover.

Due to the repetitive nature of the injection molding process, Iterative Learning Controllers (ILC) have the advantage of taking into account the performance of the machine on the previous trial and then using this information to improve the performance on the subsequent trial. The basic idea of learning control can be found in Horowitz (1993). Previous work (Havlicsek and Alleyne, 1999a,b) described the design of an Iterative Learning scheme for an IMM. The scheme was applied for the separate control of mold-filling and mold-packing trajectories. The algorithm was tested on a BOY 50M IMM. The test results showed that ILC has a strong potential to handle smooth nonlinearities and unmodeled dynamics for both filling and packing phases. However, at the end of the filling phase, the desired control variable profile changes from speed of the injection ram to polymer pressure in the mold cavity. To handle this change, two separate learning controllers were designed specifically for filling speed and packing cavity pressure control (Havlicsek and Alleyne, 1999a,b). In test implementation on a BOY 50M machine, the two separate ILCs needed to be switched over from one to the other at the point when the mold is filled. Since the 2 controllers have different reference trajectories and control outputs, the commands sent to the IMM's hydraulic valves suffer an abrupt transition during the changeover from the 1st to the 2nd ILC. This abrupt change could introduce a large transient into the system. The result could be severely degraded performance of the controller's ability to provide the right material processing characteristics. To overcome the problem, a bumpless transfer method is needed to unify these 2 stages of control.

The rest of the paper is organized as follows. Section 2 provides a brief background on the molding process. Section 3 reviews ILC control and illustrates the transient problem between mold-filling and mold-packing. Section 4 describes bumpless control algorithms and indicates the method to be used in this work. Section 5 describes the results obtained when the bumpless algorithm is coupled to the previous ILC's for control of an entire IMM cycle. A conclusion summarizes the main points of the paper.

2. SYSTEM DESCRIPTION:

The IMM used in this research is a typical "Reciprocating Screw" type IMM consisting of a mold, a barrel, a ram screw in the barrel, and the electro-hydraulic system that controls the screw movement and mold opening. The ram screw does both plasticizing and injecting during the cycle. The hydraulic system driving the ram screw has a hydraulic pump with an electrically controlled proportional flow valve and a pressure relief valve. The valves control the two hydraulic cylinders responsible for ram screw movement. Details of the relevant machine and hydraulic

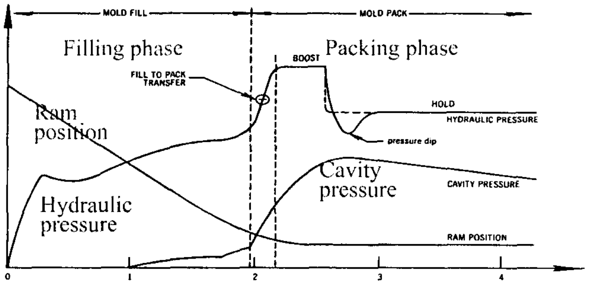
---

[1] This work supported by NSF DMI96-24837 CAREER.

0-7803-5519-9/00 $10.00 © 2000 AACC

circuitry are detailed in Havlicsek & Alleyne, (1999a) and Zheng & Alleyne (2000).

During an injection process cycle, the polymer pellets in a hopper are gravity fed into the IMM barrel. These pellets are plasticized and mixed with the polymer melt already inside the barrel. Then the ram screw moves to inject the polymer melt into the mold. When the mold is full, the ram screw maintains pressure on the polymer in the mold to compensate for the shrinkage that parts suffer during mold cooling. In the mold-filling phase, the ram position or velocity is controlled to inject the right volume of polymer into the mold as a function of time. For the packing phase, cavity pressure is controlled to maintain part weight and surface quality. A schematic of a typical cycle, which depicts the fill-to-pack transfer time in the IMM cycle, is shown in Figure 1.



Typical Injection and Packing Phase [MOOG Tech. Bulletin 145]

Fig. 1. Injection cycle phases (Thayer & Davis, 1980)

3. PREVIOUS ILC FOR IMM's:

Previous use of Iterative Learning Control (ILC) for electro-hydraulic Injection Molding Machines (IMM) demonstrated a great deal of promise in handling nonlinearities as well as unmodeled dynamics. The basic ILC algorithms can be found in (Horowitz, 1993, Messner et al 1991) and can be implemented as a feedforward controller. The resulting control law can be represented as given in Equation (1)

$$\underbrace{u_k(t)}_{\substack{\textit{present}\\ \textit{iteration}\\ \textit{input}}} = \overbrace{\underbrace{G_c(s)}_{\substack{\textit{controller}\\ \textit{transfer}\\ \textit{function}}} \cdot \underbrace{e_k(t)}_{\substack{\textit{present}\\ \textit{iteration}\\ \textit{error}}}}^{\substack{\textit{feedback}\\ \textit{term}}} + \underbrace{w_k(t)}_{\substack{\textit{present}\\ \textit{iteration}\\ \textit{feedforward}\\ \textit{term}}} \;;\; t \in \left[t_{0(k)}, t_{0(k)}+T\right] \quad (1)$$

where T is the time required to perform the trajectory and $t_{0(k)}$ is the initial time for the k-th cycle. The feedback term in Equation (1) is essential for hydraulic position control systems since the iterative adaptive learning can be applied only to plants that are already stable or have been stabilized via feedback. Since hydraulic systems contain a free integrator from valve flow to cylinder position, they are open loop unstable from input to position and must first be stabilized via feedback. The feedforward term, $w_k(t)$, in Equation (1) is determined iteratively from cycle to cycle as given in Equation (2).

$$\underbrace{w_k(t)}_{\substack{\textit{present}\\ \textit{iteration}\\ \textit{feedforward}\\ \textit{term}}} = \underbrace{w_{k-1}(t)}_{\substack{\textit{previous}\\ \textit{iteration}\\ \textit{feedforward}\\ \textit{term}}} + \underbrace{G_{learn}(s)}_{\substack{\textit{learning}\\ \textit{function}}} \cdot \underbrace{e_{k-1}(t)}_{\substack{\textit{previous}\\ \textit{iteration}\\ \textit{error}}};\; t \in \left[t_{0(k)}, t_{0(k)}+T\right] \quad (2)$$

The Iterative Learning scheme was applied in two parts for the 2 phases: filling and packing. The performance of the ILC algorithms for each phase was very effective, easily surpassing simple production controllers. In particular, the ILC algorithms were useful in tracking reference trajectories whereas the production controllers for the machine were designed more to handle set points.

However, when the two controllers were merged in the fill-to-pack transition shown in Fig. 1, the results were not quite optimal. If the controllers were connected without any modification or transition algorithm, the controller and plant states would suffer an abrupt transient in the pressure-controlled packing phase. This transient can be clearly seen in Figure 2.

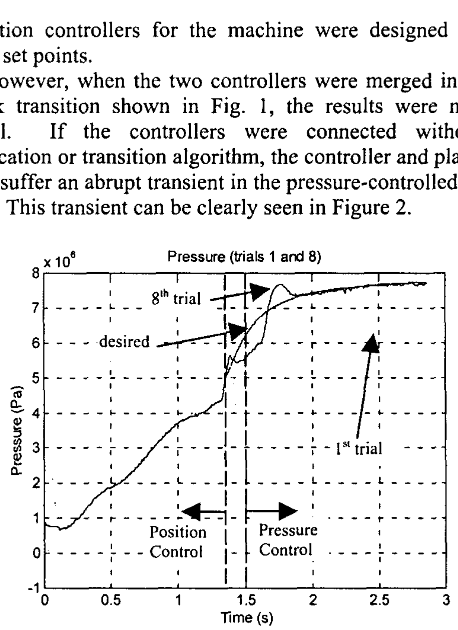


Fig.2. Line pressure (Havlicsek & Alleyne, 1999b)

After 1.35 seconds, the fill phase controller cedes control to the pack phase controller. This results in a large pressure transient on the initial cycle which leads to a large steady state error. After 8 ILC trials, the steady state error on the packing phase control is reduced to near zero. However, the learning process cannot compensate for the transient during changeover between the two controllers. This initial variation in ram pressure at the start of the pack cycle is undesirable and a simple "bumpless transfer" algorithm will be introduced to compensate for it.

4. BUMPLESS TRANSFER ALGORITHMS:

The bumpless transfer problem has been studied since the 1960's. It is defined as the transfer, or switch, between one controller acting in closed loop on a plant and a second controller waiting to take over. There are two main approaches that have been taken for the problem. The first approach is based on the online adjustment of the second controller's states at the switching time so as to keep the plant states continuous. The second category of methods uses an input-output setup to let the second controller track the first one while the first one is active and the second is waiting. In this fashion, the control signal being sent to the plant is identical between the first and second controllers. This maintains continuity of the controller inputs to the plant and generally will not produce any sudden changes of states for either plant or controller except for open-loop controllers. In implementation, the second bumpless methods utilizing controller input-output tracking are used more often owing to their ease of implementation.

The bumpless transfer problem shares the same fundamental dynamics with the anti-windup control problem. Therefore, anti-windup and bumpless transfer problems are often discussed together as AWBT (Anti-Windup and Bumpless Transfer) problems and there have been several AWBT algorithms proposed. Although the controller synthesis of anti-windup and bumpless transfer are still different, a close study could show that most of the AWBT algorithms presented in the literature are essentially the tracking loop design for the second category discussed above.

The tracking type AWBT algorithms range from basic high gain tracking loop (Uram, 1971, Campo & Morari,1990) to more sophisticated observer-based classical approach (Astrom et al., 1984). Additional contributions include the conditioning techniques (Hanus et al, 1987), refined conditioning techniques (Walgama et al, 1992), AWBT LQG optimal designs (Tyan & Bernstein, 1995), and model-based schemes (Hanus, 1988). Recent research of Campo et al., (1989) and Kothare, et al, (1994) has attempted to pose a general framework for AWBT algorithms that include all the previous approaches as special cases. In order to identify the strengths and weaknesses of each of these special cases to the generalized approach, Edwards & Postlethwaite(1998) discuss the advantages and disadvantages of each algorithm. This gives the control researcher a valuable tool with which to select an algorithm suitable for her/his particular problem.

The efforts presented in this work are an initial investigation into the bumpless transfer between fill and pack phases. Therefore, a relatively simple AWBT type of algorithm was chosen to provide a baseline for judging the improvement of transient switching responses. In this research, a modification of the high gain latent tracking algorithm (Uram, 1971, Campo & Morari, 1990) was utilized. The original algorithm was customized into the existing 2-controller ILC scheme on the BOY 50M IMM testbed. Fig. 3 shows the control diagram for the first stage of the bumpless control scheme; i.e. before the switching time, t_s. As shown in Fig 3, $\forall t < t_s$ the first controller C_A is actively controlling the plant with the following transfer function:

$$y = \frac{C_A G}{1 + C_A G} r \qquad (3).$$

The second controller C_L is working as a so-called "latent controller" to track the output u_A of the active controller. Since the controller switch connects the plant with the first controller, the output of second controller u_L is not connected to any machine input. A general Diophantine equation Feedforward/Feedback control scheme, consisting of F_L, T_L and Q_L as design polynomials, is added on top of the second "latent" controller. This tracking loop compares the output of the second controller u_L and the first controller u_A and tries to minimize the difference between them. An analytical form of the latent tracking loop in Figure 3 can be shown as:

$$u_L = \frac{F_L T_L C_L}{1 + T_L C_L Q_L} u_A + \frac{C_L}{1 + T_L C_L Q_L}(r - y) \qquad (4)$$

Since the latent tracking loop takes into account the reference signal (r) and plant output (y) as a disturbance generator, it will cause the output u_L of the second controller to asymptotically track the u_A of the first controller. The convergence of the controller tracking is based on the design polynomials F_L, T_L and Q_L. Assuming tracking transients have settled, the outputs of the 1st (active) and 2nd (latent) controllers should be identical at the time of controller transition: t_s. Since the control signal received by the plant will be identical before and after t_s, the transients associated with the switch should be minimized.

After t_s, the latent controller becomes the active controller and the previously active control is disconnected. The latent controller then works as a standard feedback controller $\forall t > t_s$.

$$y = \frac{C_L G}{1 + C_L G} r \qquad (5)$$

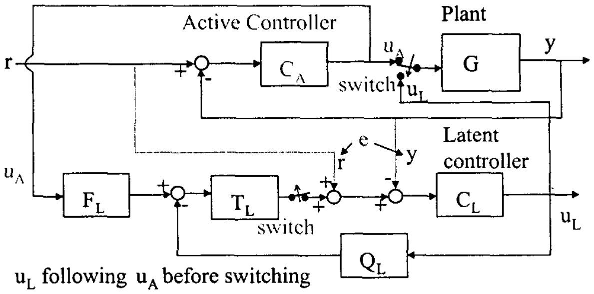


Fig 3. Latent tracking bumpless transfer, Graebe & Ahlen (1996)

If the second, or latent, controller in Fig. 3 is an open loop controller, as is typical in a transfer from automatic to manual control, the previously proposed approach might have little use. If it is open loop, the second controller will initiate its own output trajectory immediately after switching without any controller dynamics to filter the transition. Therefore, there will still be an unwanted transient. One remedy is to use a reference conditioning method to "recondition" the reference of the second controller. In this case, the modified reference will make the second controller to go back to its own trajectory gradually and smoothly. A typical implementation of this method uses the accumulated integral of the control signal in the latent tracking loop (Uram, 1971). This integrated signal could be allowed to exponentially decay by providing a zero reference to the feedback loop consisting of the second controller and the integral action. This is typically called a "reset loop". This is schematically shown in Fig. 4 which initially has switch 1 closed and switch 2 open before the switching time. Prior to the switching time t_s, the input x to the latent open-loop controller is:

$$x = (r - y) + K \int_0 (U_A(\tau) - U_L(\tau))d\tau, t \le t_s \qquad (6)$$

After t_s, when switch 1 is opened and switch 2 is closed, the zero reference in the reset loop will cause an exponential decay of the accumulated effect of u_A on the input to the latent open-loop controller. The input x to the latent controller will be:

$$x = (r - y) + e^{K \int_0^{t_s} (U_A(\tau) - U_L(\tau))d\tau} e^{-K(t - t_s)}, t \ge t_s \qquad (7)$$

Reference conditioning for OL latent controller (also called *Reset loop*)

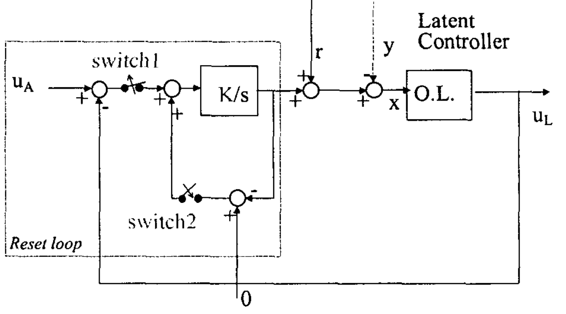


Fig. 4. Open loop latent tracking scheme for bumpless transfer.

The effect of this reset loop is demonstrated in Fig 5, where the controller output is smoothed by the addition of the exponentially decaying reset output signal.

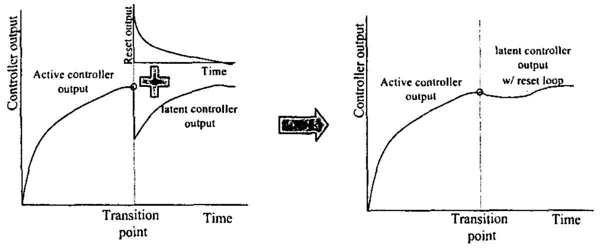


Fig. 5. Effect of reference conditioning

A disadvantage of this method is that the smoothness of the second controller output after switching will depend completely on the gain K of the integral action. This gives the control designer only a single degree of freedom for smoothing the controller transfer. The resulting limitation will be discussed again in the Conclusions.

5. EXPERIMENTAL RESULTS OF BUMPLESS TRANSFER ON IMM's:

In Havlicsek and Alleyne (1999b), the ILC scheme was experimentally applied to a production IMM in two parts. The mold-filling phase ILC consisted of a feedback controller acting in parallel with a feedforward signal identified by off-line learning. The mold-packing phase ILC consisted solely of a feedforward signal that was learned off line with no feedback component present. Details of the implementation and modeling can be found in Havlicsek and Alleyne (1999a, 1999b) along with reasons for the open loop packing control. A schematic of the two types of controllers is given below.

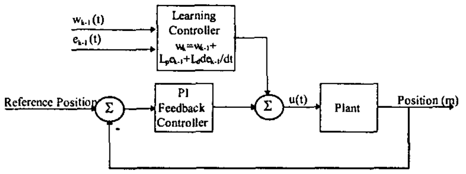


Fig. 6. "Closed loop" filling phase ILC

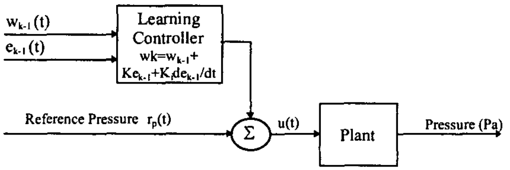


Fig. 7. "Open loop" packing phase ILC

During the filling phase, an electrohydraulic flow control valve modulates the speed of the hydraulic ram while an electrohydraulic pressure relief valve is set at some nominal relief pressure. Upon switching from fill to pack control, the flow control valve is held at a fixed position, corresponding to a relatively constant volume of hydraulic fluid flow, and the relief valve is modulated to control the pressure being applied to the mold. The control of these two valves (flow & pressure relief) constitutes the output of the two types of controllers.

Since the filling phase always precedes the packing phase for IMM cycles the position-controlled ILC in the filling phase works as the active controller while the pressure-controlled ILC of the packing phase acts as the latent tracking controller. This is diagrammed in Figure 8 where a simple integral controller (K/s) is used as the latent tracking controller. As the filling phase ILC is active, the integral latent tracking controller regulates the error between the active position controller and the latent pressure controller to zero.

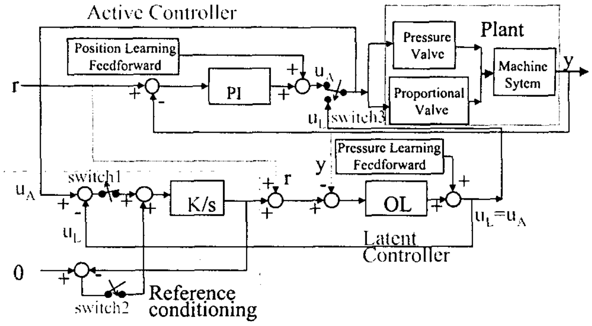


Fig. 8. IMM Implementation of bumpless transfer algorithm

The latent tracking can only force the latent pressure controller to the correct initial condition at the beginning of the packing phase. Since the latent pressure controller is open-loop (OL in Fig. 8), it can easily jump from its initial value to its own reference profile within one sampling period. This is the transient effect shown in Fig. 5. To compensate for the potential transient a reference conditioning "reset loop" is combined with the latent tracking loop to solve this problem. For algorithmic efficiency, the same integral control that is used for latent controller tracking, is utilized for the reference conditioning. At t_s the control is transferred from position (active) to pressure (latent). At this time, switch 3 is shifted from u_A to u_L and the reset loop is formed by opening switch 1 and closing switch 2. This will cause the integrated signal of the latent tracking to exponentially decay with rate 1/K as in Equation (7). The results of this approach are demonstrated as follows.

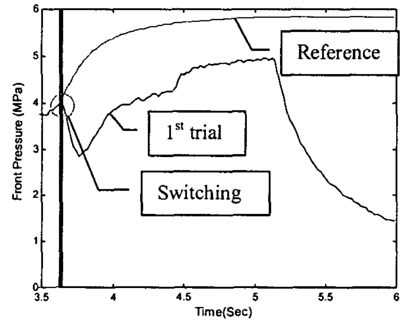


Fig. 9. 1^{st} ILC trial without bumpless transfer.

Figure 9 shows the effect on the pressure signal when the system transitions from fill control to pack control at roughly 3.6 seconds. The fill control results are of little consequence for the bumpless discussion and so they are omitted here even though the fill phase ILC is also running during the tests. Fig. 9 definitely shows a large transient in the pressure after switching, similar to Fig. 2; although it must be noted here that a different batch of polymer was used owing to the several months that elapsed between the data shown in the two figures. Fig. 10 illustrates the effect of the bumpless transfer on the switching process for several different trials of the ILC packing controller. The first trial in Fig. 10 illustrates a smoothed fill-to-pack transition right after switching, although there is a large overshoot in the initial pressure reference tracking. After 6 iterations, the controller is performing quite well. There is both a small transient in the pressure after the switch from fill to pack as well as a very good tracking of the pressure reference signal. Clearly, both the ILC and the bumpless algorithms are working well together.

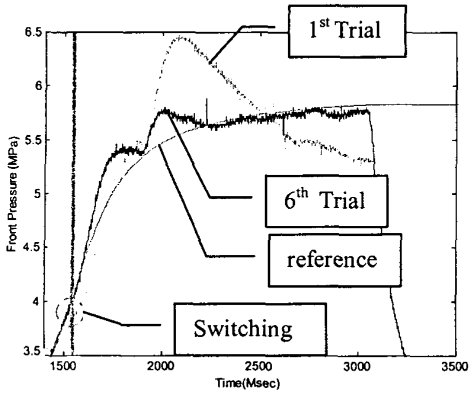


Fig 10. 1st & 6th ILC trial with bumpless transfer.

CONCLUSIONS:

In this work, the combination of ILC with bumpless transfer techniques is applied to the fill-to-pack transition control in injection molding. The ILC algorithms for separate fill phase and pack phase control were previously designed and implemented on an experimental IMM (Havlicsek & Alleyne, 1999b). These two controllers worked well for separate phases of the IMM cycle but when they were combined for an entire cycle, there were significant pressure transients at the start of the packing phase. The current inclusion of the bumpless transfer between the two ILC's has been designed and implemented also on an experimental IMM. It has been found that the simple latent tracking approach combined with a reference-conditioning algorithm provides a great deal of improvement in smoothing out the transition between the two controlled phases of the IMM cycle.

Care must be taken when choosing the gain K in the reference conditioning algorithm of Fig. 8. Too small a value of K leads to smoother transitions but larger errors for the second phase controller. Too large a K leads to very rapid transients between controller which the bumpless algorithm is attempting to avoid. Unfortunately, the value of K is currently tuned for the particular application and could be sensitive to changing system dynamics. Future work centers on a more rigorous design for the transition controller that will be robust to operating conditions.

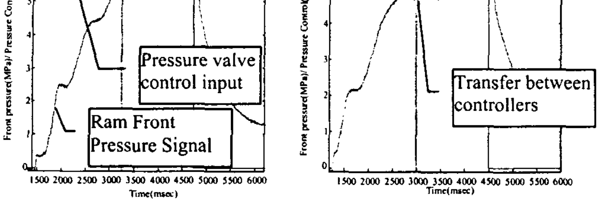


Fig 11. Bumpless transfer with different K

ACKNOWLEDGEMENT

The authors would like to thank Prof. Charles Tucker for the use of his experimental IMM in this research.

REFERENCES

1. Astrom, K. J. and Wittenmark, B., "Computer Controlled Systems Theory and Design," Prentice Hall, Englewood Cliffs, NJ, 2nd ed. 1984.
2. Campo, P. J., and Morari, M., "Robust control of processes subject to saturation nonlinearities," *Comput. Chem. Engng.,14, 343-358,* 1990.
3. Campo, P. J., Morari, M., and Nett, C. N., "Multivariable anti-windup and bumpless transfer: a general theory," *Proceedings of ACC'89*, 2, 1706-1711, 1989.
4. Edwards, C. & Postlethwaite,I., "Anti-windup and Bumpless-transfer Schemes," *Automatica*, V. 34, No.2, 199-210, 1998.
5. Gao, F., W. I. Patterson, M. R. Kamal, "Cavity Pressure Dynamics and Self-Tuning Control for Filling and Packing Phases of Thermoplastics Injection Molding," *Polymer Engineering and Science*, Vol. 36, No.9, May 1996.
6. Hanus, R., Kinnaert, M., and Henrotte, J-L., "Conditioning technique, a general anti-windup and bumpless transfer method," *Automatica*, 23(6), 729-739,1987.
7. Hanus, R., "Anti-windup and bumpless transfer: A survey," *Proc. 12th IMACS World Congress on Scientific Computing, 59-65, 1988.*
8. Havlicsek, H., and Alleyne, A., "Nonlinear Modeling of an Electrohydraulic Injection Molding Machine," *Proceedings of the 1999 American Controls Conference*, pp. 171-175, San Diego, CA, June 1999
9. Havlicsek, H., and Alleyne, A., "Nonlinear Control of an Electrohydraulic Injection Molding Machine via Iterative Adaptive Learning," *Proc. of the 1999 American Controls Conference*, pp. 176-181, San Diego, CA, June 1999
10. Horowitz, R., "Learning Control of Robot Manipulators," *ASME Journal of Dynamic Systems, Measurement, and Control*,Vol. 115, pp. 402-411, June, 1993
11. Kothare, M. V., Campo, P. J., Morari, M. , and Nett, C. N., "A unified framework for the study of anti-windup designs, " *Automatica*, 30(12), 1869-1883, 1994.
12. Messner, W., Horowitz, R., Kao, W., Boals, M., "A New Adaptive Learning Rule," *IEEE Transactions on Automatic Control*, Vol. 36, No.2, pp.188-197, 1990.
13. Graebe, S.F., and Ahlen, A., "Bumpless Transfer," The Control Handbook, pp. 381-388, CRC Press, 1995.
14. Thayer, W.J., & Davis, M.A., "Controls for Injection Molding of Thermoplastics," Moog Technical Bulletin No. 145, Moog Inc., East Aurora, NY, 1980.
15. Tsoi, H. and Gao, F., "Fuzzy logic controller for injection ram," *Processing Annual Technical Conference-ANTEC, Conference Proceedings*, V1, 641-644, 1998.
16. Tyan F, and Bernstein, D., "Anti-windup compensator synthesis for systems with saturation actuators," *International Journal of Robust and Nonlinear Control*, V5, 521-537, 1995.
17. Uram, R., "Bumpless Transfer under Digital Control", Control Eng., 18(3), 59-60, 1971.
18. K. S. Walgama, S. Ronnback and J. Sternby, "Generalization of conditioning technique for anti-windup compensators," *IEE Proceedings-D*, V139, n2, March 1992.
19. Zheng, D. and Alleyne, A., "Control-Oriented modeling of an injection molding machine including the fill-to-pack transition," *Proc. of the 2000 ASME IMECE*, Orlando, FL, Nov. 2000.