MULTI-CAVITY PRESSURE CONTROL IN THE FILLING AND PACKING STAGES OF THE INJECTION MOLDING PROCESS

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ABSTRACT

Cavity pressure has been recognized as a critical process parameter for the injection molding of high quality plastic parts. Recent developments in injection molding process technology have enabled closed loop control of cavity pressure at one point in the mold. In this paper, a scheme is described which enables the simultaneous control of cavity pressure at multiple locations in both multi-gated parts and/or multi-cavity molds. This has been achieved by the addition of dynamic valves in the melt delivery system, each of which can be independently controlled to meter the flow and pressure of the polymeric melt to its portion of the mold. The development and capabilities of the control system are presented, demonstrating the feasibility of simultaneous multi-cavity pressure control in both the filling and packing stages of the injection molding process. Due to space limitations, however, the ability of multi-cavity pressure control to improve process capability and molded part quality are presented in a companion paper.

INTRODUCTION

Injection molding of thermoplastics has emerged as the premier vehicle for delivering high quality, value added commercial products. Continued global competitiveness has increased standards for product capability and quality while requiring reduced product development time and unit cost. Despite advanced design methods and new process technologies, it is becoming apparent that the injection molding process is neither flexible nor robust enough to reliably meet these industry requirements. The lack of robustness is evidenced by the long product development cycles, excessive tooling costs, low process yields, and inferior product quality.

It is the polymer state (pressure, temperature, and morphology) which directly determine the molded part quality. As such, recent technology development has rightly focused on closing the loop between the machine parameters and the polymer conditions. If achieved, these advanced control systems would provide increased molded part consistency. However, even perfect control, i.e. the ability to profile the inlet melt temperature and pressure, will be unable to satisfy industry's increasingly stringent requirements. Due to its physical configuration, conventional injection molding is inherently a one degree of freedom process. The temperature and pressure distribution in the cavity is inextricably linked to the inlet melt conditions and the process dynamics forced by the mold geometry. As such, there is no way to simultaneously control the polymer melt at multiple locations inside the mold – there are no degrees of freedom available for adjustment as necessitated by good design and manufacturing practice (1).

As thermoplastic materials continue their thrust into advanced technical applications, control of only one degree of freedom will become even more constricting, prohibiting thermoplastic materials from entering many advanced applications. The risks of proving out the injection molding process for a technical application with multiple stringent requirements are too excessive. In fact, several industry managers have testified that “we are starting to see the migration of customers to other manufacturing processes for time-critical applications.”

This paper describes a means to combine closed loop cavity pressure control with multiple degrees of freedom. The closed loop control provides heightened molded part consistency, while the multiple degrees of freedom provide enormous enhancement of process flexibility. These degrees of freedom can be used to compensate for complex material properties, reduce or eliminate input variation, and adapt to changing production requirements. With this production stage flexibility, the product time to market will inevitably be reduced while ensuring acceptable levels of product quality and process yields. Moreover, the improved process flexibility and capability permit greater risk and innovation in the conceptual design stages which may ultimately result in previously unattained product capabilities. Ultimately, this research provides the product designer additional freedom while simplifying the tasks of the tooling engineer and machine operator.

RELATED WORK

Prior to 1972, most injection molding machines controlled the injection pressure through the use of a pressure relief valve between a hydraulic accumulator and the injection unit's cylinder. At the start of the cycle, hydraulic flow from the accumulator would push the ram forward at an arbitrary rate. After the cavity was filled, the pressure relief valve would maintain a holding pressure until the part was packed and solidified. Machines with more advanced control systems could use two relief valves to enable a time-based switchover from higher injection pressures to lower holding pressures during solidification. Electrically modulated pressure relief valves were introduced in 1975 to provide solid state control of the injection pressure throughout the molding cycle (2).

The first modern computer-controlled injection molding machine was described by Carl Ma in 1974 while employed by Cincinnati Milacron (3). As shown in Figure 1, Ma identified the critical process variables, and designed a control system for each process stage. This work led to the development of modern control systems for injection molding machines and enabled current closed loop control systems for ram velocity and injection pressure (4).

Control systems using proportional and servo-valves to obtain closed loop control of ram position and hydraulic pressure were common by 1980. While closed loop ram velocity and injection pressure control significantly improved the process capabilities of injection molding, the output state variables in the cavity which determine product quality remain uncontrolled. In this sense, **injection molding is an open loop process once the material leaves the barrel of the molding machine**. When quality issues arise, there are no easily modified process parameters which may be used to directly control state variables and resolve the problem.

One outcome of this previous work was the recognition of cavity pressure as a critical process variable, indicative of the thermo-mechanical history which ultimately determined the molded part's properties. By monitoring cavity pressure as an input signal, closed loop cavity pressure control could automatically compensate for variations in melt viscosity, injection pressure, and hydraulic subsystems to achieve a consistent process and uniform product attributes. Mann first described this control scheme in 1974 and employed an iterative algorithm to achieve a functional process using modulated pressure relief valves (5).

Abu Fara (6) developed a process control model by relating the cavity pressure response to open loop perturbations. Srinivasan (7) later used these models to propose a learning controller for closed loop cavity pressure control. Gao, Nunn, and Chiu (among others) have more recently used modern control techniques to achieve acceptable closed loop control of cavity pressure at one location in the mold cavity (8, 9, 10).

The use of closed loop cavity pressure control has not yet become common even though significant improvements in process repeatability have been reported (11). With more robust sensor technology and less expensive computer control systems, however, closed loop cavity pressure control is beginning to be used in applications demanding heightened process repeatability. Since the flow characteristics of the mold are largely unchangeable once tooled, closed loop cavity pressure control provides control at only a single point. Thus it constitutes only a limited form of quality control to reduce the effects of input variation.

More sophisticated model-based control systems have yielded only marginal improvements in process capability and product quality. In these control schemes, analytical models are used to generate real-time estimates of unmeasurable process variables such as residual stress, shear rate, or fiber orientation. Computations are based on measurable inputs such as injection velocity, melt temperature, and cavity pressure. The control system can then use the analytical models in its control law to determine the molding machines dynamics to optimize part properties, many of which could only be ascertained after molding, if at all.

Many model-based controllers have been developed. Shankar (12) was first to develop a non-linear model-based control system in 1978 to optimize ram velocity with a discrete iterative control method. Agrawal et. al. (13) have reviewed several recent process control strategies and proposed a system which maintains consistent density throughout the part, based on an equation of state for the material's compressibility behavior. Based on this work, several adaptive model-based controllers have recently been developed to resolve machine dependency and increase the product quality and consistency (10, 14). The difficulty with these control strategies is that they do not provide any inherently new process capabilities. At best, these systems attempt to maximize the molded part properties (strength, dimensions, etc.) by controlling the polymer state at a single point.

Another potential benefit of model-based control is the resolution of multiple conflicting goals, given the constraints of the molding process. In 1991, Seaman (15) devised a machine controller to monitor the molded part’s quality and maintain the process on an optimal trade-off boundary to avoid performance degradation while trying to improve one of the part’s characteristics. For instance, Seaman utilized the procedure shown in Figure 2 for a spiral mold tool to prevent flashing while minimizing the cycle time and part to part deviation in flow length. Similar research is currently integrating the analysis capabilities of process simulations to optimize process control (16).

PROCESS DEVELOPMENT

Suh (1) hypothesized that independence of functional requirements should be maintained in any system design or manufacturing process. There should be an independent, adjustable parameter for each critical feature or specification in the design. In the molding of a complex part, all of the part specifications become interdependent due to the tightly coupled dynamics of the injection molding process. Unless the design specifications are fairly loose, it may be impossible to manufacture acceptable parts.

As applications have become more complex, the number of functional requirements have increased without relaxation of part specifications. As previously discussed, the degrees of freedom necessary to manufacture these parts do not exist in the injection molding process. When problems are encountered late in the development process, this limitation means that the engineer must utilize degrees of freedom available only through tooling and conceptual design changes. These late changes are costly and time consuming while providing no guarantee of problem resolution. Indeed, important features are often sacrificed to guarantee a product launch.

System Design

The goal of injection molding process control is to specify the pressure and temperature distribution across the entire cavity. There are many possible concepts for adding the necessary degrees of freedom but the most generic approach is to provide a means for instantaneously modifying the flow resistance in each branch of a runner system. As shown in Figure 3, this is accomplished by a set of strategically located, variable impedance valves, each with a rapid-response hydraulic actuator. The valves are designed with an adjustable annular clearance between a tapered valve stem and outer sleeve. Since the resistance to flow is determined by the annular gap between the valve stem and the mold wall, axial displacement of the valve stem can be used to selectively vary the flow rate and pressure drop through each valve. When used in a closed loop control system, this method can provide simultaneous control of multiple cavity pressures.

This system implementation introduces three new characteristics into the molding process:

1) The independent control of each valve allows the pressure and flow in multiple regions of the cavity to be decoupled. Previously, changes aimed at improving one area of the part could result in detrimental effects elsewhere in the cavity since process changes could not be controlled independently. With this process, the flow through each valve can be controlled independently, bringing extra degrees of freedom to the molding process.

2) The capabilities of this system can be leveraged by dynamic re-positioning of the valve within the molding cycle. This strategy can be used, for instance, to specify one set of valve positions to profile flow rates in the filling stage followed by a completely different set of valve positions to profile pack pressures. Using the dynamic capabilities of the new system, it will be shown that each valve brings several degrees of freedom to the molding process, i.e. decoupling of the filling and packing stages.

3) The dynamic capabilities of this process allow the valves to be quickly controlled in response to feedback from process sensors in the mold cavity, thus providing closed loop control of the cavity state variables which directly determine the product quality. Variation in molding machine input parameters, machine behavior, or material properties can be dynamically compensated to produce consistent parts. Moreover, the control of cavity variables directly enables the use of pressure measurements as a process control

technique for automated detection of quality problems. This could eliminate the need for manual inspection of part quality in many circumstances. Since the dynamics of the molding machine are decoupled from the cavity, details of molding machine performance now become insignificant!

Figure 4 is a control representation of the system architecture. In this ideal representation, the control system receives a quality target and part specifications for the application being molded such as part dimensions and allowable tolerances. Using simple empirical and analytical relations, these specifications are converted to desired cavity pressure distributions to be produced during the molding process. The control system then compares the desired and observed cavity pressures, calculating and generating command signals for real-time control. The command signals generated by the control system are transmitted to multiple hydraulic servo-valves in the molding machine. These servo-valves provide pressurized melt to the inlet of the feed system as well as hydraulic flow to each of the feed system's actuators. These actuators in the feed system move the valve stems to meter the pressurized melt to each area of the cavity. As the process continues, process sensors provide the control system with the feedback from the current valve positions and cavity pressures.

Process Model

A process model was developed to aid in control system development. The goal of the process model is to capture the essential process dynamics of the filling and packing stages of the molding process: the melt propagation in the filling stage; the melt compressibility in the packing stage; the flow resistance due to the valve position; and, the dynamics of cavity pressure dependent upon the previous effects. The following simplifying assumptions are utilized to obtain a model of minimal complexity.

The process model is based upon laminar Hele-Shah flow for a purely viscous, Newtonian fluid under isothermal conditions. The Hele-Shah approximation is applicable to the momentum equation due to the relatively long characteristic length of the flow direction compared to the thickness direction. The characteristic Reynolds numbers are very small, $\vartheta(10^{-3})$, so inertial effects may also be omitted from the momentum equation. The flow regions are considered fully developed and both the unsteady state and gravitational force effects are ignored due to negligible local acceleration. As a consequence of these assumptions, the pressure varies only in the principle flow direction so the flow dynamics are governed solely by the shear-stress effects of the polymer melt.

The process model further assumes isothermal conditions which simplify the numerical solution for control purposes, otherwise fairly complex finite element/finite difference methods would be necessary in the simulation. This assumption, however, will result in an underestimation of the effects of thermal volumetric shrinkage as the polymer cools and contracts in the packing stage. To provide for an accurate model of the flow rates during the post-filling stage, the specific volume throughout the cavity is modeled with an empirical equation of state dependent upon cavity pressure and cavity temperature; the cavity temperature is estimated without performing heat transfer calculations by assuming a constant empirical cooling rate. Again, the goal is to develop a minimal complexity control model which captures the vital dynamics of the system – such assumptions will provide reasonable estimates of aggregate process dynamics.

The model also assumes that there is no interaction between multiple valves, i.e. that the dynamics of one valve do not affect the injection pressure or cavity pressures in other areas of the mold. Moreover, the model assumes that the servo-valves have negligible response time compared to the process dynamics, that there is negligible leakage and friction in the control actuators, and that the hydraulic fluid is incompressible. Finally, the process model utilizes a series of rectangular channels to model the flow dynamics through various mold elements.

All these assumptions could be refined by developing a more complex process model. However, the resulting model would introduce further non-linear and time-dependent behavior which would increase the difficulty of interpretation and control system development without substantially increasing the benefit of the model. The stated assumptions lead to a simple process model which captures the aggregate process dynamics and is useful in control system development. The accuracy of these assumptions will be re-examined later.

The governing mass and momentum equations for laminar flow in a rectangular strip have previously been well developed (17) and will not be repeated here to preserve space to discuss multi-cavity pressure control strategies. However, this laminar flow model must be coupled with the molding machine dynamics to develop a useful model of the process. Again, the goal is to develop a control model which captures the most significant relationships between the machine dynamics and cavity pressure. As previously mentioned, second order effects (such as servo-valve dynamics, hydraulic leakage, etc.) are not considered. The principle dynamics being modeled include:

- the acceleration of the ram, dependent upon input hydraulic pressure and transient injection pressure;
- the effect of ram velocity on flow rate and cavity pressure; and

- the effect of valve stem volumetric displacement on cavity pressure.

There are two principle forces acting on the machine ram and valve stems which determine the motion of these machine elements: [1] hydraulic pressure within the hydraulic actuator and [2] the pressure in front of the ram or valve stem in contact with the melt. Assuming an ideal hydraulic control system, the force balance on the ram and valve stem becomes:

$$F_{ram} = M_{ram} a_{ram} = P_{hyd} A_{hyd} - P_{inj} A_{ram} \tag{1}$$

$$F_{valve} = M_{valve} a_{valve} = P_{hyd} A_{valve} - P_{cav} A_{valve} \tag{2}$$

where P_{inj} and P_{cav} are the injection pressure and cavity pressure, respectively. It should be noted that if the product of hydraulic pressure and area of the hydraulic actuator is large compared to product of melt pressure and area of the valve, then the actuation force is much greater than the reaction force due to the melt pressure. In this case, the ram or valve would accelerate quickly to a velocity limited by the volumetric capacity of the machine's hydraulic pump. Since the valve stem area is very small, ~1 cm^2, compared to its hydraulic actuator, ~30 cm^2, the process model simplifies and the valve stem velocity can be specified as an input to the system with negligible acceleration dynamics.

Once the acceleration of the ram and specified velocity of the valve stem are known, the resulting melt flow rates may be determined. The ram displacement is the principle source of flow but the valve stem displacement affects the flow dynamics through two mechanisms. First, the location of the valve stem determines the resistance to flow which subsequently determines the injection pressure and the ram velocity. Secondly, the time varying volumetric displacement of the valve stem is also a source (or sink) of flow. In the packing phase, the volume displaced by the valve stem can be considerable compared to the volumetric changes due to compressibility in the cavity. These effects make valve stem displacement an effective, though difficult to regulate, method for direct control of cavity pressures. The conservation of mass then states:

$$\dot{m}_{ram} = \dot{m}_{flow} + \dot{m}_{valve} \ , \qquad (3)$$

which is the primary linkage between the machine dynamics and the flow dynamics. The resulting control model is shown in Figure 5. As shown in this diagram, the ram acceleration, a_{ram}, is determined solely by the input hydraulic pressure and the current injection pressure. The flow rate into the cavity is determined primarily by the ram velocity. However, valve stem displacement can either increase or decrease the melt flow rate into the cavity depending upon its direction of movement; solidification of the melt can only reduce the melt flow. The sum of these three flows advances to the melt front.

There is a significant change in the system dynamics when the melt flow reaches the end of the cavity. At this point, an impermeable boundary condition is applied at the melt front, i.e. $R_{cavity} \to \infty$, and the melt front is not permitted to advance. The process dynamics in the packing stage are quite different than those of the filling stage – the flow due to the ram displacement becomes negligible, increasing the significance of flow due to compressibility and valve displacement.

The system described in Figure 5 is clearly not linear. In fact, the valve position, x_{valve}, only affects the flow resistance through the non-linear term R_{val}. For a small incremental time step compared to the process dynamics, the change in valve position and flow length is small.

This allows calculation of the flow resistance in the valve and cavity at that moment for the system described in equation [4], below. The matrix elements are then updated and the resulting flow rates and melt pressures recalculated. Numerous iterations are performed until the simulation is finished.

$$\begin{bmatrix} \dot{v}_{ram} \\ \dot{P}_{cav} \\ \dot{x}_{val} \\ \dot{L}_{flow} \end{bmatrix} = \begin{bmatrix} \frac{-R_{val} \cdot A_{ram}^2}{M_{ram}} & \frac{-A_{ram}}{M_{ram}} & 0 & 0 \\ \frac{A_{ram} \cdot \beta}{V_{cav}} & \frac{-R_{cav} \cdot \beta}{V_{cav}} & 0 & \frac{-\beta_T \cdot \beta \cdot w \cdot h}{V_{cav}} \\ 0 & 0 & 0 & 0 \\ 0 & \frac{1}{w \cdot h \cdot R_{cav}} & 0 & 0 \end{bmatrix} \begin{bmatrix} v_{ram} \\ P_{cav} \\ x_{val} \\ L_{flow} \end{bmatrix} + \begin{bmatrix} \frac{A_{hyd}}{M_{ram}} & 0 \\ 0 & \frac{-A_{val} \cdot \beta}{V_{cav}} \\ 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} P_{hyd} \\ v_{val} \end{bmatrix} \tag{4}$$

The model has a total of nine parameters as listed in Table 1: three parameters are related to material properties while six constants are related to physical dimensions of the molding machine and mold cavity. While the physical parameters will vary with the molding machine and mold geometry, they can be estimated with confidence. The values listed in Table 1 are for the material, molding machine, and mold geometry used in the experimental portion of this research.

This research utilized the material properties of an unfilled, medium viscosity polycarbonate (Lexan™ 121 resin, GE Plastics). Polycarbonate is an amorphous thermoplastic with well understood rheological and compressibility behavior. The material properties listed in Table 1, however, are gross estimates of this material's actual behavior in molding. The plant model considers the effect of compressibility and thermal volumetric shrinkage during the filling and packing stages of the injection molding process utilizing this bi-linear model. In these stages, the thermoplastic melt is primarily liquid – the packing stage ends when flow has solidified and both the rheological and compressibility assumptions are clearly invalid. This simple model provides an acceptable model for estimating the aggregate dynamics of the process. More complex material and process models could be utilized, but would further complicate the numerics and non-linearities seeking to be understood.

Control Model

The physics of the molding process provides formidable challenges to control system development. Even with all the assumptions regarding material properties and process physics, the plant model remains highly non-linear. The primary input to the system, valve stem velocity, only indirectly affects the plant behavior. Moreover, the dynamics of the process are time dependent – not only do they change with valve position but with time as the polymer flows through the cavity. Indeed, the filling and packing stages of the process exhibit very different process dynamics, each stage must be addressed in control system development. Some necessary performance characteristics of the control system are:

- tracking of time-varying cavity pressure profile;
- rejection of sensor noise and actuator hysteresis;
- compensation for machine, material, operator variation;
- guaranteed stability;
- robustness to unknown inputs and unmodeled plant dynamics; and,
- transferable to other molding machines, feed system designs, and mold geometries.

One potential method for controlling cavity pressure would be to directly profile the valve position across the filling and packing stages. For instance, a valve position of 7 mm could be utilized in the filling stage to achieve a cavity pressure profile around 10 MPa/sec followed by a move to 3.5 mm to obtain a packing pressure of 30 MPa. Without an automatic control algorithm, however, this would involve direct operator intervention and expert knowledge of the process physics to achieve and maintain the desired process performance. Moreover, all effects of machine, material, and operator variations would be transmitted through the feed system to the cavity. Since cavity pressure is not directly controlled, it is evident that the consistency of the injection molding process would not be improved.

Proportional, integral, derivative (PID) controllers are ubiquitous in the process control industry. In fact, PID controllers are currently used to control ram velocity, barrel temperature, coolant temperature – nearly every process variable within the injection molding process. Unfortunately, PID control is unsuitable due to the rapidly varying, non-linear behavior of the cavity pressure dynamics. Figure 6 shows the root-locus of the process model when the mold cavity is approximately 50% full. A stable response can only be ensured with a very conservative set of gains, but then the control response would be so slow as to result in unacceptable system dynamics and defective parts.

The alternative to controllers with fixed feedback gains is to utilize adaptive control techniques. Many adaptive techniques have been developed for control system design – reviews are available in the literature (18, 19, 20). The distinguishing feature of adaptive control systems is that the control behavior adapts to changing process dynamics, i.e. the control system redesigns itself as the process changes. Adaptive control schemes were first developed in the 50's to improve aircraft flight dynamics at varying altitudes. Model reference adaptive control (MRAC) is currently the most prevalent research area within the adaptive control field and may be positioned in various forms such as $H\infty$, optimal control, self tuning controllers, variable structure systems.

Unfortunately, all accessible adaptive control techniques require the process dynamics to be approximately linear with a well-defined structure. Less significant non-linear dynamics are not modeled and later compensated by a robust controller design. Control design of nonlinear systems with invertible nonlinearities are currently an active field of research. Since cavity pressures within the injection molding process are nonlinear and these dynamics can not be linearized, most MRAC and optimal control techniques do not apply.

The control design problem is not intractable, however. Adaptive gain scheduling is the oldest and simplest form of adaptive control – it is also the most widely used of all adaptive algorithms by far (21). Moreover, the process model lends itself well to this form of control since gain scheduling permits the use of several different control algorithms based on the current operating conditions. The main burden of developing a system which successfully utilizes gain scheduling is to identify the proper control design to be used in each stage and effecting a smooth transfer between stages during operation. Within a stage, the controller properties are fixed – this enables the control system to be designed off-line and then tuned on-line for each stage before production use.

As previously described, the plant model exhibits very different process dynamics in the filling and packing stages, each which demands different types of valve actuation. In the filling stage, excellent control of flow rates are provided with the valve in primarily open positions. The flow through the valve is much greater than the flow displaced by the valve movement, so excellent dynamic response should be provided by rapid valve actuation. In the packing stage, however, the flow rates are small compared to the flow displaced by valve movement. Control of packing pressures necessitates the valve to be in a semi-closed position at the start of the packing stage and respond slowly to changes in cavity pressure. With adaptive gain scheduling, the control system can utilize completely different control algorithms in the filling and packing stages. Figure 7 illustrates the adaptive control structure used for closed loop cavity pressure control of one valve in the filling and packing stages.

Implementation

The control system was developed in the C programming language, utilizing a 90 Mhz Pentium® processor. An internal data acquisition board (AT-MIO-16L-9, National Instruments) monitored the nine incoming signals listed below in Table 2. All of the instrumentation was selected to provide 0 to 10 volt analog signals at a sampling frequency of 200Hz. As will later be demonstrated, this range of voltage and data sampling rate provided ample process detail without excess sensitivity to signal noise. The control system employed a software development kit (Lab Windows for DOS version 2.3a, National Instruments) to provide high level graphical interface and data I/O subroutines. As the molding cycle progresses, the control system analyzes the process data and issues -10 to +10 volt analog signals through the data acquisition board to the two hydraulic servo-valve controllers (Vickers EEA-PAM-535-A-30, Paul-Munroe Sweetland, Whittier, CA). These controllers provide 0 to 10 amp currents at 24 VDC to the proportional hydraulic valves on the molding machine to reposition the valves in the feed system.

The molding trials were performed at GE Plastics' Commercial Development Center (Pleasanton, CA) utilizing a 400 ton molding machine (390MJ-100, Mitsubishi Heavy Industries Ltd., Tokyo, Japan). The machine's hydraulic system provided a source of hydraulic power for control of the feed system. Proportional servo-valves (Vickers KFDG-4-V-5, Paul-Munroe

Sweetland) mounted on the machine's hydraulic manifold replaced the two directional control valves normally used for core pulls during the molding process.

Since the molding machine's injection hydraulics were not directly controlled by the control system, the ram velocity and injection pressure were specified by the process technician. Generally, an injection profile was utilized which provided consistent, excessively high injection pressures to the polymer melt. The closed loop cavity pressure control system then varied the valve resistance to obtain the desired cavity pressures. Better performance could have been obtained if the controller regulated the injection unit's servo-valve, but this task was outside the scope of this research.

The feed system shown in Figure 3 is a custom hot manifold developed by Kona Corporation (Gloucester, MA) specifically for this research. A base manifold (VG-33SR single bar manifold) served as the starting design platform. Melt temperature and pressure transducers (MTX-935 and PT465XL-30M, respectively, Dynisco Instruments, Sharon, MA) were installed in a heated sprue bushing to obtain the melt inlet conditions. The most significant modifications involved the accommodation of miniature position transducers (HydraStar HS-1000, Data Instruments, Boston, MA) to monitor the dynamic valve stem location. Together with their signal amplifiers (SP-50, Data Instruments), these inductance transducers provided position data accurate to 0.01 mm with a response time less than 1 mSec. Accommodating the position transducers required a re-design of the hydraulic actuator as well as the addition of an auxiliary plate behind the hydraulic plate.

Several critical design parameters of the feed system are listed in Table 3. With the given bore of the hydraulic actuators and flow rate capacity of the hydraulic proportional valves, the maximum speed of the valve stem is approximately 30 cm/sec. Including the acceleration dynamics of the valve, the valve stem can move across its full range of motion in approximately 0.100 sec – much faster than will generally be required during the molding process.

VALIDATION

Tests were carried out to demonstrate that closed loop, multi-cavity pressure control is the most effective strategy for improving the flexibility and consistency of the injection molding process. Figure 8 illustrates an actual closed loop cavity pressure response (solid trace) for a typical input pressure profile (dotted line). For this research, an input profile is defined by the filling stage start time, the slope of cavity pressure in the filling stage, and the level of cavity pressure in the packing stage. The closed loop and adaptive control algorithms will dynamically vary the valve positions to obtain the desired profile shown in the figure.

In this particular example, the valve was opened at 0.5 seconds to initiate the flow. At 1.0 seconds, the melt enters the cavity, as indicated by the time at which the pressure transducer registers a cavity pressure over 1.0 MPa. If the cavity pressure entered the cavity more than 0.1 seconds away from the desired entry time (as indicated by the horizontal error bar), the adaptive algorithm would readjust the valve timing in the subsequent shot to correct the error. Once the melt has registered on the pressure transducer, the closed loop control algorithm then maintains the cavity pressure on the designated slope as shown in Figure 8 between 1.0 and 2.5 seconds.

Just prior to the switchover between the filling and packing stages, the control system moves the valve to a nearly closed position for control of the packing stage. The sharp rise in cavity pressure at 2.5 seconds is due to the displacement of flow ahead of the closing valve stem which generates a temporary increase in the flow rate into the cavity. The quick decay at 2.6 seconds occurs when the valve stops moving and flow rates have been significantly decreased due to increased flow resistance through the nearly closed valve. The final rise in cavity pressure at 2.7 seconds occurs when the cavity is completely full and the flow rates through the valve stabilize.

The timing of the valve's switchover determines the level of cavity pressures just after the switchover to the packing stage. If the cavity pressure is more than 5 MPa above or below the desired pack pressure (as indicated by the left vertical error bar), then the switchover occurred to early or late (respectively) and will be adjusted in the subsequent shots by the adaptive control algorithm.

Finally, the pack pressure level is measured by the asymptotic cavity pressure prior to the end of the packing stage (as indicated by the right vertical error bar). If the pack pressure does not conform to the desired value, valve stem positions will be adjusted in subsequent shots to improve the pack pressure levels.

Controller Tuning

The closed loop, multi-cavity pressure control capability demonstrated in Figure 8 has never before been achieved. Previous process developments have had only partial success since the process dynamics are immutable once determined by the mold steel in the conventional molding process. Even though this feed system design enables extra degrees of freedom with which to alter the process dynamics, the closed loop and adaptive control mechanisms are not trivial problems. The successful development of the control logic is now described.

FILLING STAGE

The filling stage of the injection molding process is characterized by a fairly homogeneous polymer melt, high flow rates, and increasing flow resistance. Due to these qualities, the control strategy for the filling stage utilized proportional-derivative feedback control of cavity pressure. The general form of this control is:

$$u_{valve} = K_P\left(P_{cav} - P_{des}\right) + K_D\left(P'_{cav} - P'_{des}\right) \tag{5}$$

This type of control law will open or close the valve as needed to deliver the desired filling stage response. As shown in Figure 9, there is quite a wide range of proportional gains, K_P^P, for which the system is stable, between 0.5 and 2.5 mm/sec/MPa. Moreover, the system stability was not affected by changes in mold temperature, melt temperature, or hydraulic pressures. The stability of control system did, however, depend on the input pressure profile. For slopes of cavity pressure greater than 30 MPa/sec, reducing the proportional gains enhanced system stability.

PACKING STAGE

Control of cavity pressures in the filling stage was relatively easy. The packing stage, however, is characterized by very low flow rates determined solely by volumetric changes due to the compressibility and cooling of the polymer melt. These low flow rates will make control of the packing stage considerably more difficult since small displacements of the valve may substantially effect the cavity pressures in the packing phase. As a first attempt, the same control law from the filling stage was utilized, albeit with much smaller proportional gains to minimize the valve displacement, i.e.:

$$u_{valve} = K_P\left(P_{cav} - P_{des}\right) + K_D\left(P'_{cav} - 0\right) \tag{6}$$

Figure 10 illustrates the poor control in the packing stage using PD control of pressure. In this plot, the desired packing pressure is 25 MPa, as indicated by the dotted line. The control system has transitioned into the packing stage at 5.3 seconds. At this point, the cavity pressure is below the desired level so the control system opens the valve at 5.4 seconds. This results in an immediate drop in cavity pressure due to negative volume displacement caused by the valve stem's retraction. The cavity pressure then begins to increase. By 5.6 seconds, the cavity pressure is at the desired level and the valve position has leveled off. However, the cavity pressure continues to rise so the control system slowly closes the valve. This act of slowly closing the valve increases the cavity pressure due to the positive displacement produced by the valve movement. The increase in cavity pressure further drives the control system to fully shut the valve by 6.2 seconds. The cavity pressure does not decay until the melt in the cavity contracts due to thermal shrinkage.

Given the strong interaction which develops between the cavity pressure and the valve displacement, a natural solution might be to use the valve as a piston to drive flow utilizing positive feedback of cavity pressure. If the cavity pressure is below the desired level, then shut the valve to force more melt into the cavity and increase cavity pressure. This control law can be represented as:

$$u_{valve} = -K_P\left(P_{cav} - P_{des}\right). \tag{7}$$

Unfortunately, this is not an effective means for control because of the limitations on valve travel. As shown in Figure 11, the valve has transitioned into the packing stage at 5.25 seconds. The control system recognizes that the cavity pressure is below the desired level and, as such, closes the valve to force more material into the cavity. The cavity pressure responds favorably but then begins to slowly decay as the melt in the cavity solidifies. The control system tries to maintain the cavity pressure by further closing the valve but the attempt is ineffective. By 6.2 seconds the valve is fully closed and the cavity pressure is free to decay.

Due to the undesired linkage between the valve displacement and cavity pressures in the packing stage, the control system was forced to utilize strong proportional position control with weak negative feedback of cavity pressures:

$$u_{valve} = K_P^P\left(P_{cav} - P_{des}\right) + K_D^P\left(P'_{cav} - 0\right) + K_P^X\left(X_{valve} - X_{pack}\right). \tag{8}$$

In this scenario, a valve position is estimated for the packing stage. If the cavity pressure deviates significantly from the desired level, then the base valve position is changed in subsequent shots to obtain acceptable packing pressures. The valve then remains at a nearly constant position during the packing stage. This strategy, unfortunately, is incapable of eliminating disturbances within a single molding cycle. However, it does provide effective removal of systematic disturbances such as material, machine, and operator variation. The process behavior shown in Figure 8 was generated using this control law.

Process Performance

An adaptation mechanism was implemented to govern the transition between the control of the filling and packing stages which have been described. Altogether, there are three variables which must be determined: valve initiation time for the start of the filling stage, valve transition time between the filling and packing stages, and default valve position for the packing stage. Each of these parameters is estimated before the molding process begins and is updated each cycle with new process information according to the previously defined rules. Figure 12 plots the cavity pressure traces for four sequential shots, starting at the beginning of a molding trial.

As shown in Figure 12, the initial estimates provide a late transition to the packing stage and a large overshoot in the cavity packing pressure (1). The adaptive algorithm recognizes this pressure spike and reduces the transition time to obtain the response shown in trace two (2). The cavity pressure again overshoots resulting in another reduction in transition time to obtain trace three (3). The transition time is excellent. However, the control system recognizes that the pack pressure decays below the desired level of pack pressure. As such, the adaptive algorithm increases the valve position in the packing stage to obtain the pressure response shown in trace four (4). This response is within the defined tolerance limits of the control system. The part is designated as 'good' and the process parameters are used for the subsequent shot. If a process change were to occur during the manufacture of a batch of parts – a change in process conditions or material properties, for instance – the adaptive system would take corrective actions to produce and maintain the desired process dynamics.

The performance of the adaptive system might best be measured by the number of shots required for the molding process to converge to an acceptable response. To examine the process performance, forty molding trials were performed for different part geometries, wall thicknesses, process conditions, and input profiles. For each molding trial, the number of shots required to obtain good parts was recorded. Figure 13 displays the frequency distribution for all these molding trials.

In every single case, the adaptive algorithm did converge to an acceptable process response. The number of shots which were required depended largely on the accuracy of the initial estimate. In two cases, the initial estimates of process parameters were very good and resulted in production of good parts on the second shot. In two other cases, the initial estimates were very poor, requiring more than a dozen shots to obtain good parts. On average, the adaptive algorithm converged in about eight shots after startup. This performance is satisfactory considering the large number of parts which are commonly produced in a batch of molded parts.

The adaptive algorithm is itself a form of feedback control. The speed of convergence may be increased significantly by increasing the gain, i.e. the amount with which each process parameter is adjusted between shots. However, increased adaptive gains were found to occasionally lead to severe oscillations in the process parameters as well as an unacceptable process response. Accordingly, a conservative set of adaptive gains was used to ensure consistent convergence across a variety of mold geometries, process conditions, material properties, and input profiles.

CONCLUSIONS

The cavity pressure distribution has been widely recognized as a critical process variable for delivering molded part quality and consistency. However, the temperature and pressure distribution in the cavity have been inextricably linked to the inlet melt conditions and the process dynamics determined by the mold geometry. As such, the conventional molding process does not permit simultaneously control the polymer melt at multiple locations inside the mold, let alone specify the entire cavity pressure distribution to effect the molded part properties.

This paper described one method for implementing simultaneous multi-cavity pressure control. The described system utilized multiple valves in the feed system to deliver extra degree of freedom for the part designer, tool designer, and molder. To effectively control the polymer melt at each valve, an adaptive gain scheduling was developed. Implementation and testing of this system demonstrated the ability to locally control the cavity pressure near each valve. A companion paper will present the ability of multi-cavity pressure control to improve the process capability and molded part quality.

As the careful reader might have inferred in the last section, the system's ability to control cavity pressure in the packing phase was severely limited by the counter-active effect of melt volume displacement due to the valve movement. This undesired effect forced the development of the fairly sophisticated control scheme described in this paper. A second implementation of this system is currently under development to investigate commercial feasibility for a printer housing with four valves while enhancing the process dynamics through valve and hydraulic redesign.

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Table 1: List of Model Parameters

CONSTANT	DESCRIPTION	ESTIMATED VALUE
β_{melt}	Bulk modulus of melt	-4.2e-4 cm^3/g/MPa
β_T	Coefficient of thermal contraction	4.1e-4 cm^3/g/C
η	Shear viscosity of thermoplastic melt	400 Pa Sec
A_{hyd}	Cross-sectional area of hydraulic cylinder	100 cm^2
A_{ram}	Cross-sectional area of ram	10 cm^2
A_{valve}	Cross-sectional area of valve stem	1 cm^2
h	Wall thickness of mold cavity	0.2 cm
M_{ram}	Mass of ram	60 kg
w	Width of mold cavity	5 cm

Table 2: Incoming control signals

molding machine start
injection pressure
melt temperature
four cavity pressures
two valve positions

Table 3: Design parameters of feed system

Parameter	**Value**
actuator area	15 cm^2
valve stem diameter	1 cm
length of valve taper	1.5 cm
angle of valve taper	8°
length of valve travel	3 cm

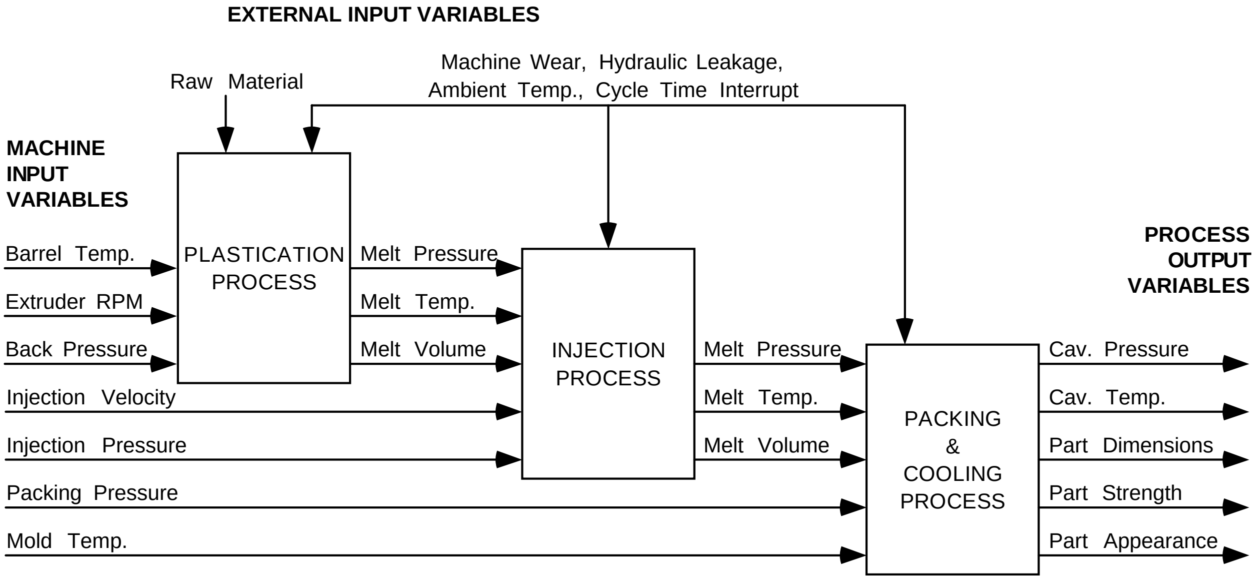

Figure 1: Ma's Injection Molding Process

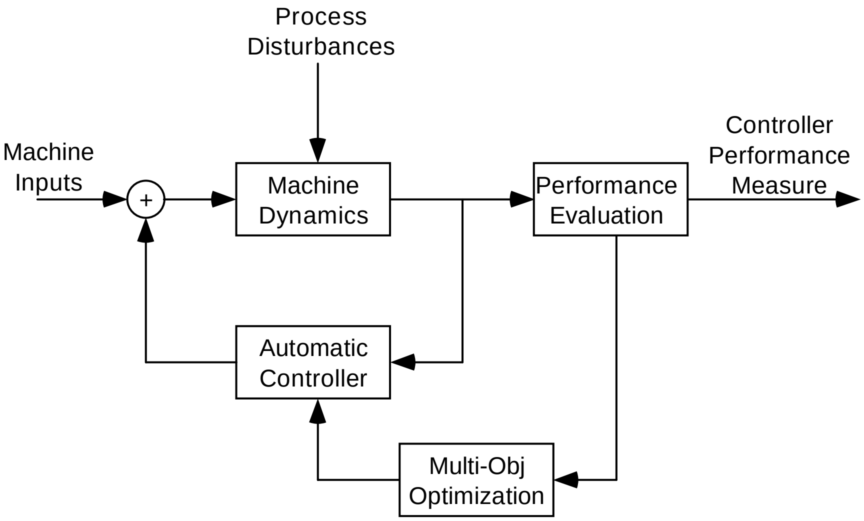

Figure 2: Model-Based Molding Process Optimization (Seaman)

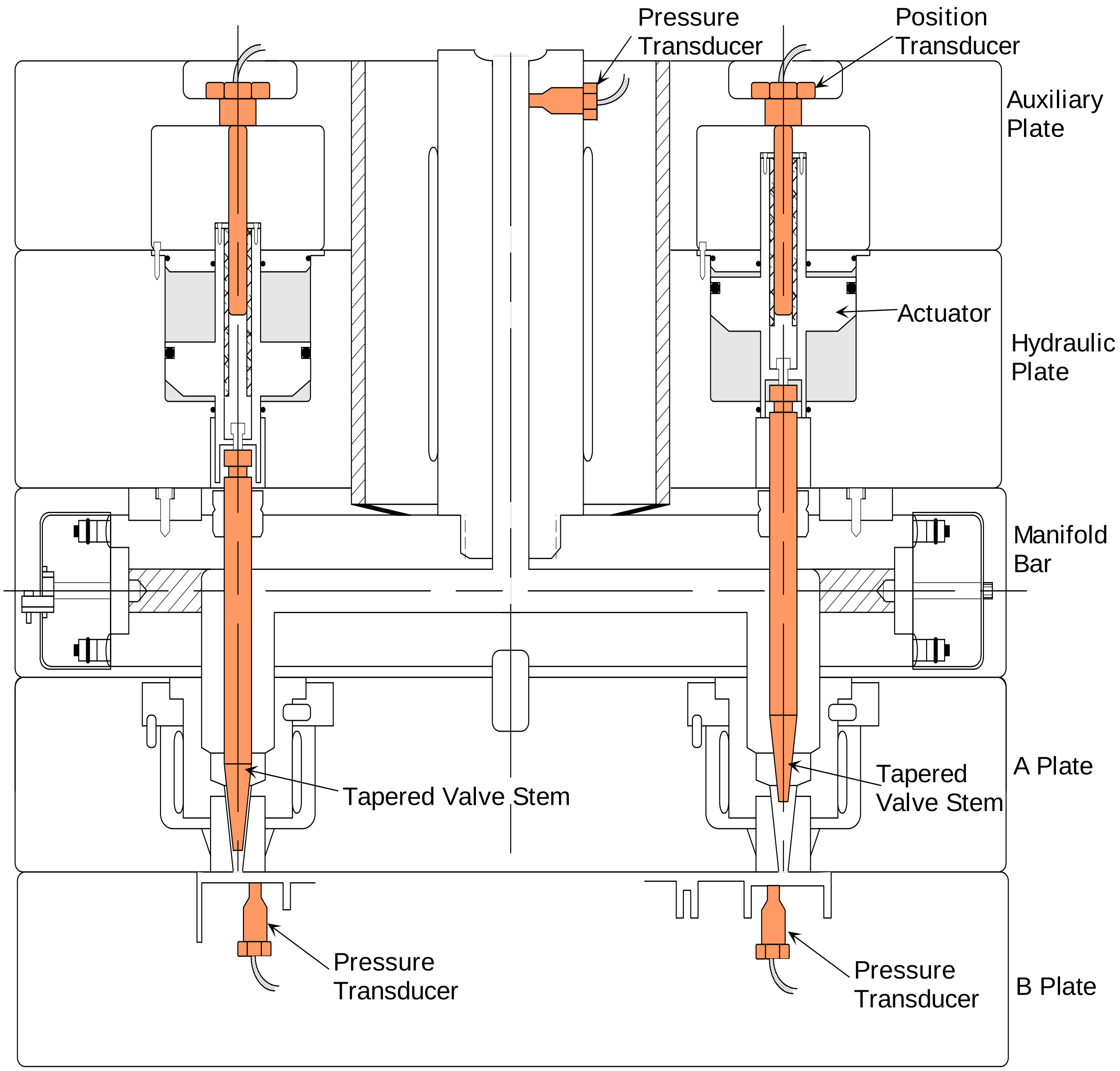

Figure 3: Multiple Independently Controlled Valves

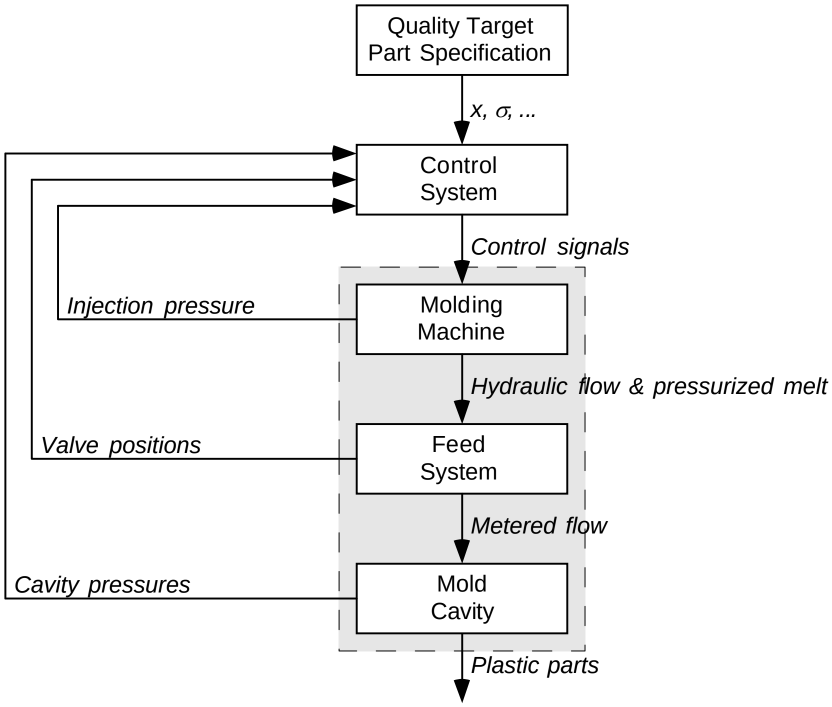

Figure 4: Control Representation of System Architecture

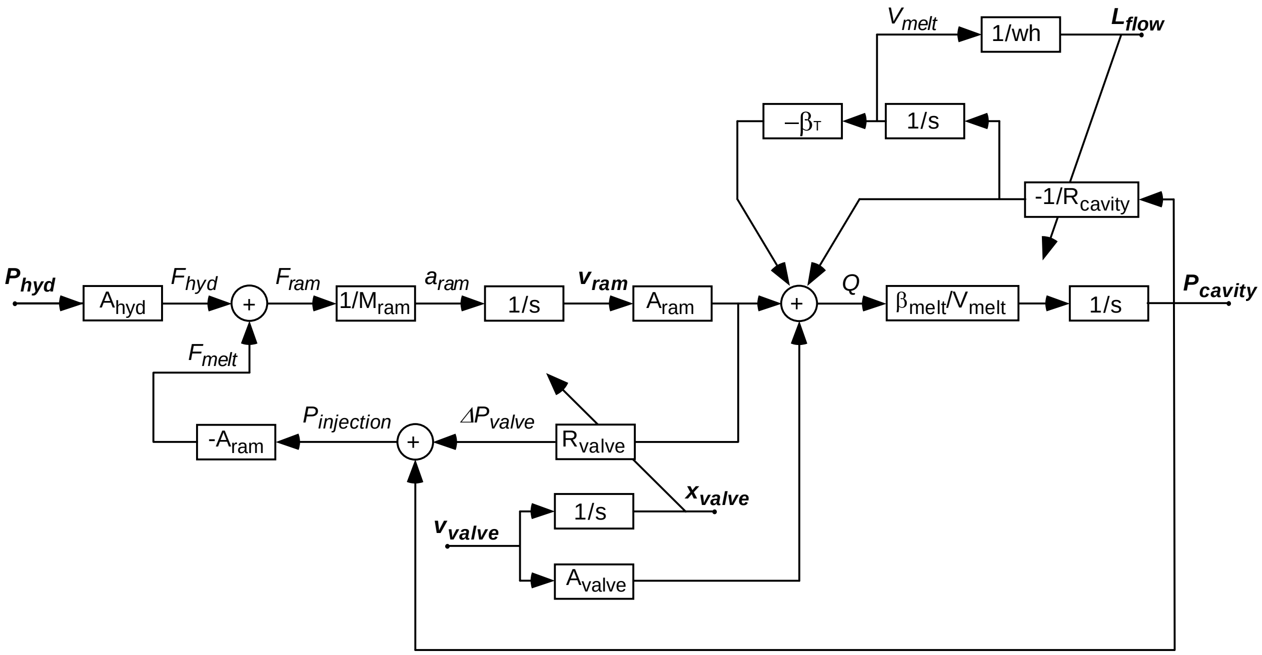

Figure 5: Process Control Model

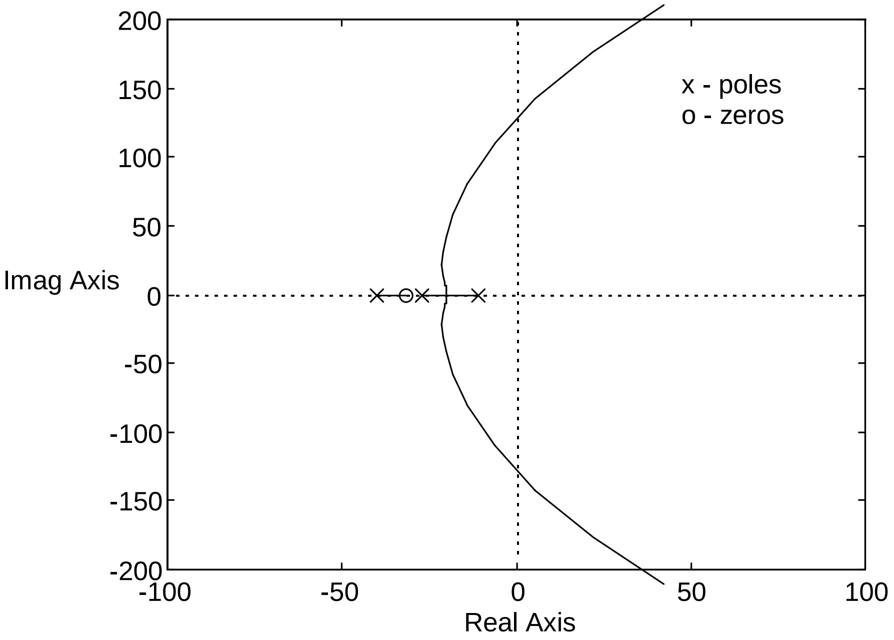

Figure 6: Closed Loop Response at 50% through the Filling Stage

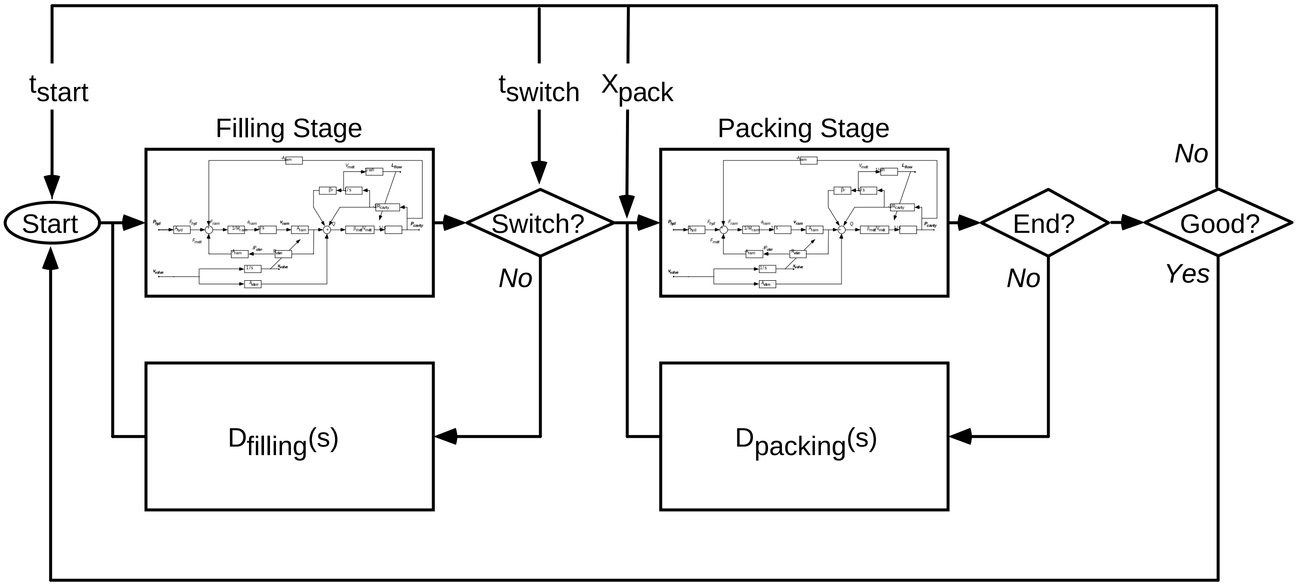

Figure 7: Control Design for Each Valve

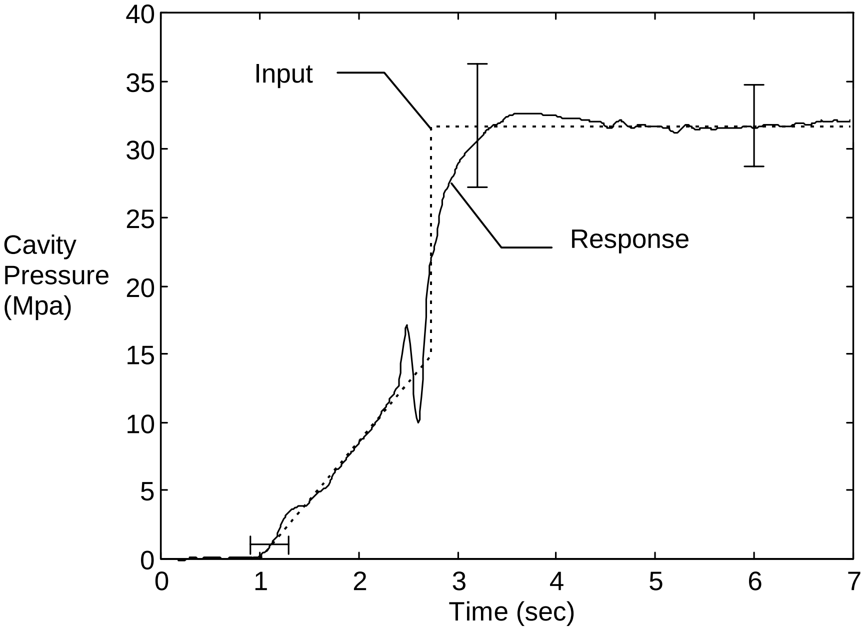

Figure 8: Cavity Pressure Profile with Measurement Indices

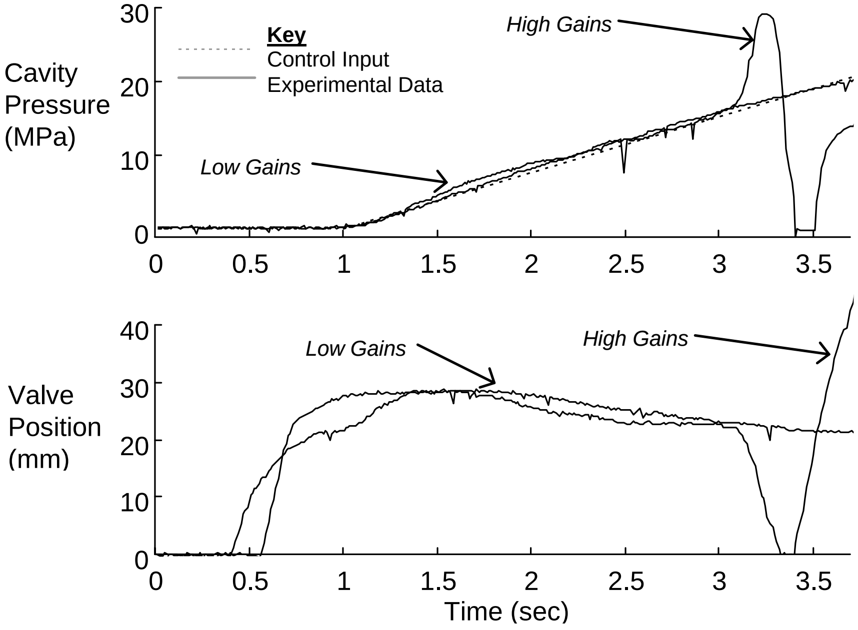

Figure 9: Cavity Pressure Profiles during the Filling Stage

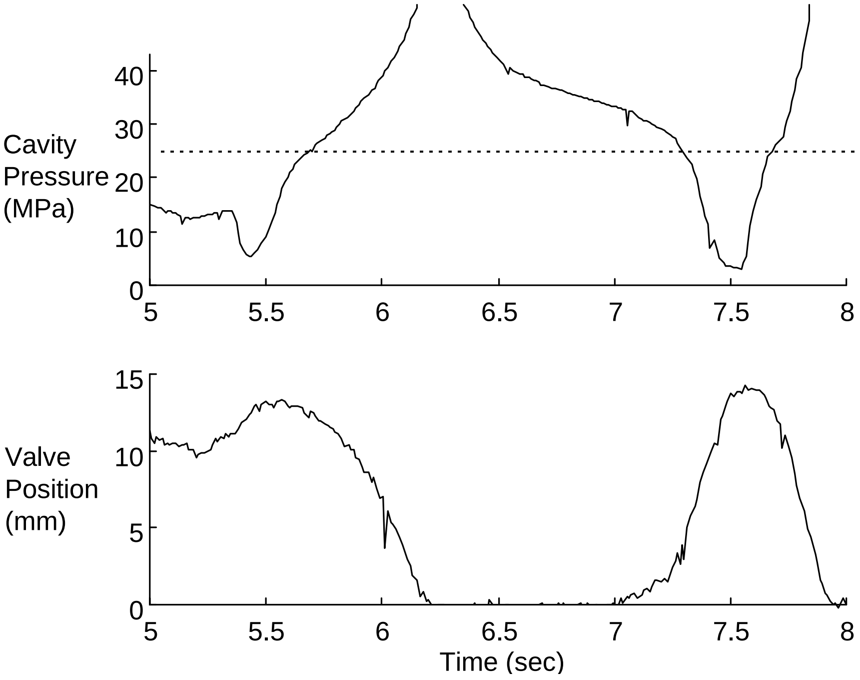

Figure 10: Cavity Packing Pressure Response using PD Control

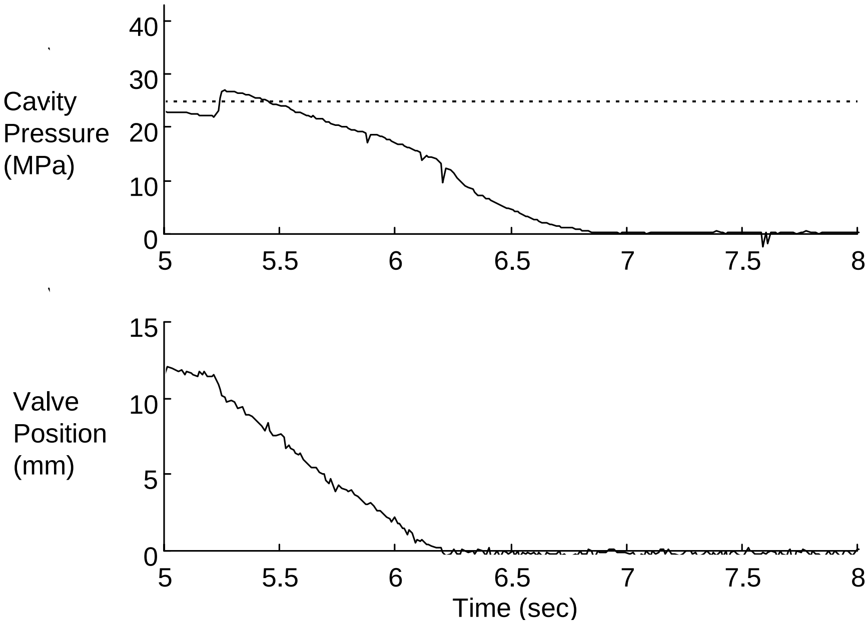

Figure 11: Cavity Pressure Response using Positive Feedback Control

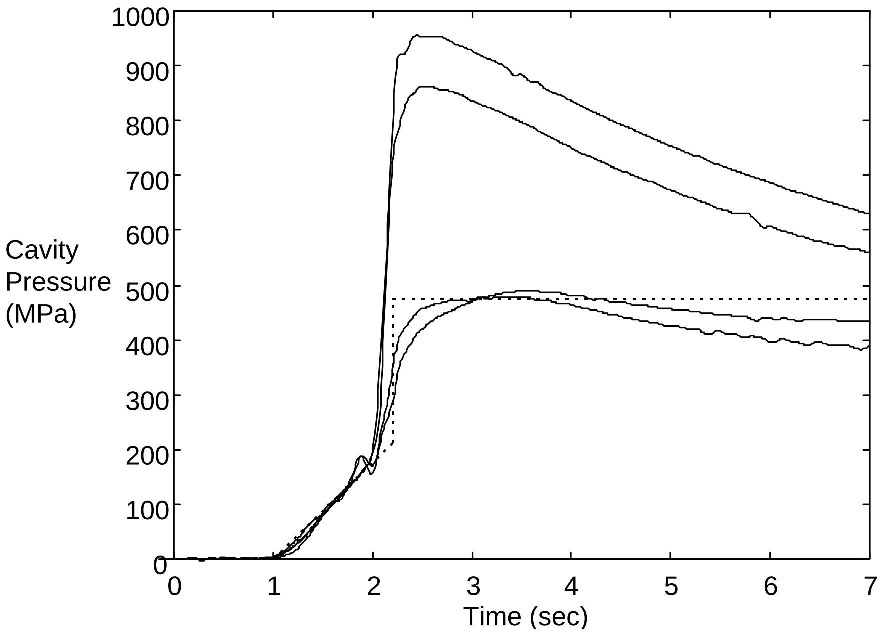

Figure 12: Typical Cavity Pressure Convergence

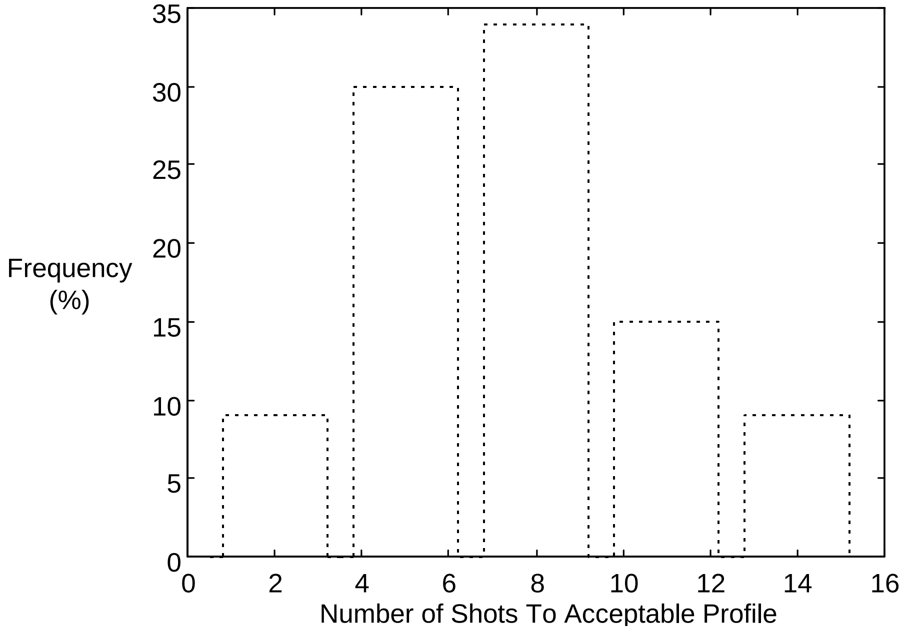

Figure 13: Number of Shots Required for Profile Convergence