DIRECT ADAPTIVE CONTROL OF RESIN TRANSFER MOLDING

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ABSTRACT

Resin Transfer Molding (RTM) is a manufacturing process that involves injection of liquid resin into a closed mold cavity containing preset fiber mats and a subsequent curing stage. Mold filling is a crucial stage for quality part productions. In order to automate production and minimize the formation of defects, control of mold filling is needed. In this paper, direct adaptive control strategy is presented for RTM mold filling control in order to account for variations in fiber preform permeability. Using this control strategy, it is shown that the actual filling pattern can successfully be controlled to follow the designed filling pattern.

KEY WORDS: Resin Transfer Molding, RTM, Adaptive Control

1. INTRODUCTION

Resin Transfer Molding (RTM) is a manufacturing process that produces high-strength and lightweight polymer composite parts for wide range of aerospace, automotive, and satellite applications. RTM process involves injection of a liquid resin into a closed mold cavity containing preset fiber mats (also called perform). Subsequent curing of the liquid resin forms a net-shape polymer composite part with good dimensional tolerances. RTM process has good potential for mass-production manufacturing [1-3].

Mold filling is a crucial stage in RTM. Defect-free parts cannot be obtained without successful consistent mold filling. However, consistent mold filling may be difficult to achieve in industrial setting. This is due to the influence of preform permeability on filling pattern as well as the uncertainty in permeability and race tracking phenomenon. Consequently, wide range of variations in filling patterns has been observed, which causes part-to-part variation in quality. Hence, there is a need for realtime RTM process control to achieve consistent mold filling and ensure part quality.

RTM mold filling control concept falls into two categories: open-loop control and closed-loop control. In open-loop control, an off-line filling simulation or calculation is performed to identify the optimum placement and operation of injection ports and air vents. Open-loop control is easier to implement and, hence, often used as the first attempt to the problem. The effectiveness of the open-loop control relies on an accurate model of RTM filling process. This seems to not to be a problem because many filling models have been developed with good results [4-16]. In open-loop RTM control strategy, one of the common starting points is that the preform permeability in the mold is known [17-22]. However, this is not the case in real situation. Hence, open-loop control may not bring satisfactory performance.

The key in achieving consistent mold filling by control is the prompt and proper response to permeability variation in realtime. In open-loop control, everything in the controller is fixed prior to the filling, which cannot adjust to any disturbance in permeability. In contrary, closed-loop control provides the adaptability to disturbance in perform permeability. With closed-loop control, the inlet variables such as inlet flow rate or pressure can interact with control variables (such as filling front position) in realtime in order to obtain the desired filling pattern. Several closed-loop control methods have been found in previous works such as a closed-loop controller for a 1-D analog of the Liquid Composite Molding (LCM) process [23] where the control strategy was based on the online estimation of conductivity of fiber mat. The instant filling front position was obtained from inlet flow rate. A desired filling path (i.e., filling front position vs. time) was defined a priori. The control objective was to let the real filling front follow the desired one. The results obtained from this closed-loop control strategy appeared to have improved compared with those from the open-loop control. Other studies have proposed a Sequential Logic Control (SLC) algorithm for closed-loop control of RTM process [24]. With tracking the filling front position, operations such as opening and closure of the injection ports, converters, and vents were performed during filling process in order to adjust filling pattern. The SLC algorithm was based on a 1-D flow. In 2-D situation, the mold was divided into several sub-domains so that the flow in each sub-domain could be regarded as one-dimensional. Thus, in a complex 2-D mold, the number of injection ports, converters, and vents would be big and their arrangement and operation could become quite complex. Artificial neural network has also been applied to RTM process to form closed-loop control [25-33]. A neural network is a system that imitates the human brains. Before it functions, the system has to be trained. During the training phase, a set of input data is given to the system as training data; the neural network then adjusts itself in order to come up with the desired outputs. The system's performance is constrained by its training phase. Two factors are important in this phase. One is that in order for the system to work well in the real practice, the training data has to reflect the real practice. Another is that for a better performance, the system must be trained with enough data. To get enough valid training data is a very time-consuming process.

In this paper, an adaptive control strategy is proposed for the purpose of mold filling control in RTM process. Adaptive control is a special type of closed-loop system using regulators with non-linear varying parameters that are determined by the feedback from the performance.

2. PROBLEM DESCRIPTION

The RTM filling problem investigated in this paper is as follows: A tube-shaped mold with unit cross-sectional area contains the fiber preform. Resin is then pumped into the mold from one end with injection pressure P. At any instant t, the mold is partially filled. The interface between the filled and unfilled region is assumed to be planar. The position of the filling front is measured by the distance from the injection gate and is designated as S as shown in Figure 1.

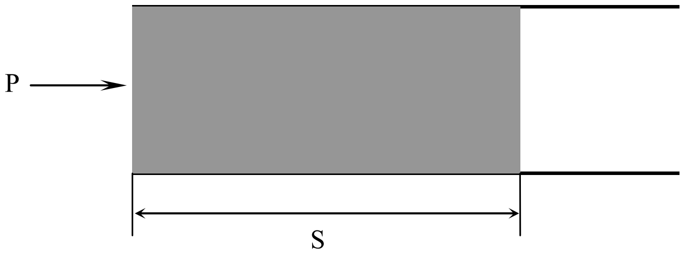

Figure 1. Schematic of RTM tube mold filling problem.

Assume that we expect the interface to move with uniform speed during the mold filling stage and the designed flow front movement is given as:

$$S = V \cdot t \tag{1}$$

where V is designed flow front velocity and t is filling time. In this work, the above-mentioned filling process is simulated and the instant filling front position is calculated. The objective of the paper is to develop adaptive control strategy such that *under a wide range of variations in perform permeability* the simulated filling front movement can be controlled to follow the designed one as expressed in equation (1).

For the purpose of mold filling control, a relationship between instant filling-front position and the injection pressure need to be established. Resin flow in RTM process can be regarded as a flow in porous media. It can be described by Darcy's law, i.e. the resin velocity can be expressed as

$$V = -\frac{k}{\mu}\frac{\partial P}{\partial S} \tag{2}$$

where k is fiber permeability, μ is viscosity of resin and $\partial P / \partial S$ is the pressure gradient at flow front. When taking k and μ as constant, we have

$$P(t) = \frac{V^2 \mu}{k} t \tag{3}$$

Thus, with the knowledge of k and μ, instant injection pressure can be set up in order to obtain a uniform filling front movement. An open-loop control based on equation (3) is applied to the proposed RTM filling control. In order to illustrate the performance of the open-loop control, several permeability distributions in fiber performs are assumed to simulate the possible situations occurring in real practice [23]:

1. Nominal permeability: k_0
2. Low constant permeability: $k_L = k_0 / 2$
3. High constant permeability: $k_H = 2k_0$
4. Slow varying permeability: $k_{LP} = k_0 \cdot 2^{\sin(2\pi x / L)}$

   where L is mold total length and x is the coordinate in mold filling direction.

5. Fast varying permeability with high frequency:

$$k_{SP} = k_0 \cdot 2^{0.5 \cdot \sin(6\pi x / L) + 0.5 \cdot \cos(2\pi x / L) + \sin(2\pi x / L)}$$

The aforementioned permeability distributions are shown in Figure 2 in dimensionless form when taking L as 0.4 meters. Nominal permeability is taken as 2.0×10^{-9} m^2.

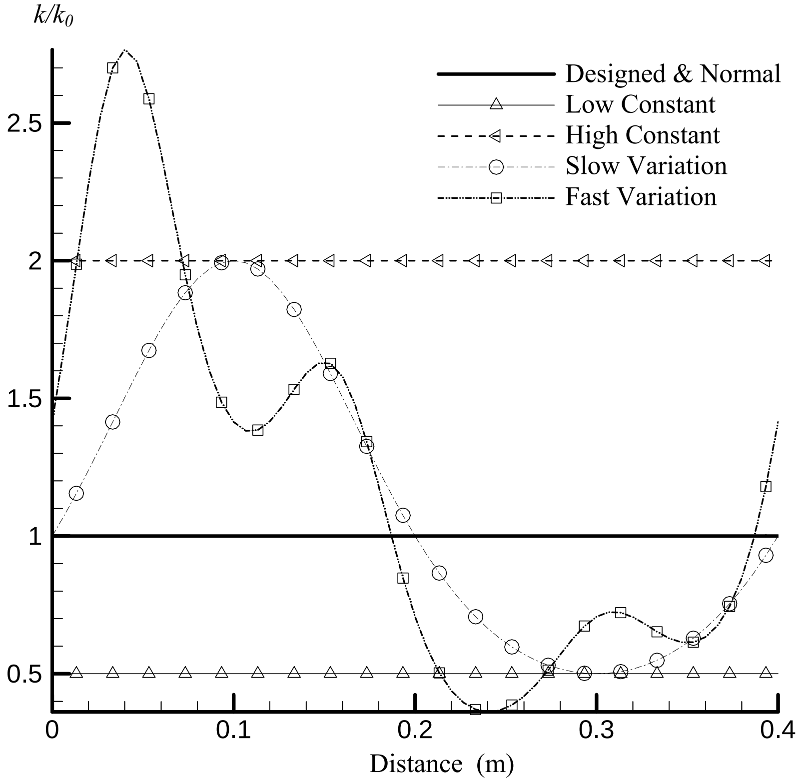

Figure 2. Different permeability distributions in perform; k_0 is the nominal permeability.

3. OPEN-LOOP CONTROL OF MOLD FILLING

Isothermal filling is assumed and resin viscosity is taken as 10 Pa.S [12]. The designed filling front velocity V is set to 0.01 m/s [23]. The open-loop controller is tuned with nominal permeability. The resulting instant flow front positions under the open-loop control are shown in Figure 3. The solid line in the figure represents the designed filling front movement. When fiber permeability is taken as the nominal value (k_0), the flow front under open-loop control follows the designed path exactly. However, when fiber permeability varies, open-loop control fails in regulating filling front position to follow the designed one. For instance, in the case of low constant permeability, the filling front moves much slower than the designed movement due to higher preform resistance to resin flow. The filling front always lags behind the designed position and the filling takes longer time. In the situation with high constant permeability, filling front always stays in front of the designed position and as a result, mold filling takes less time than designed. In the cases with varying permeability, filling fronts vary compared to the designed positions, sometimes staying ahead and sometimes lagging behind.

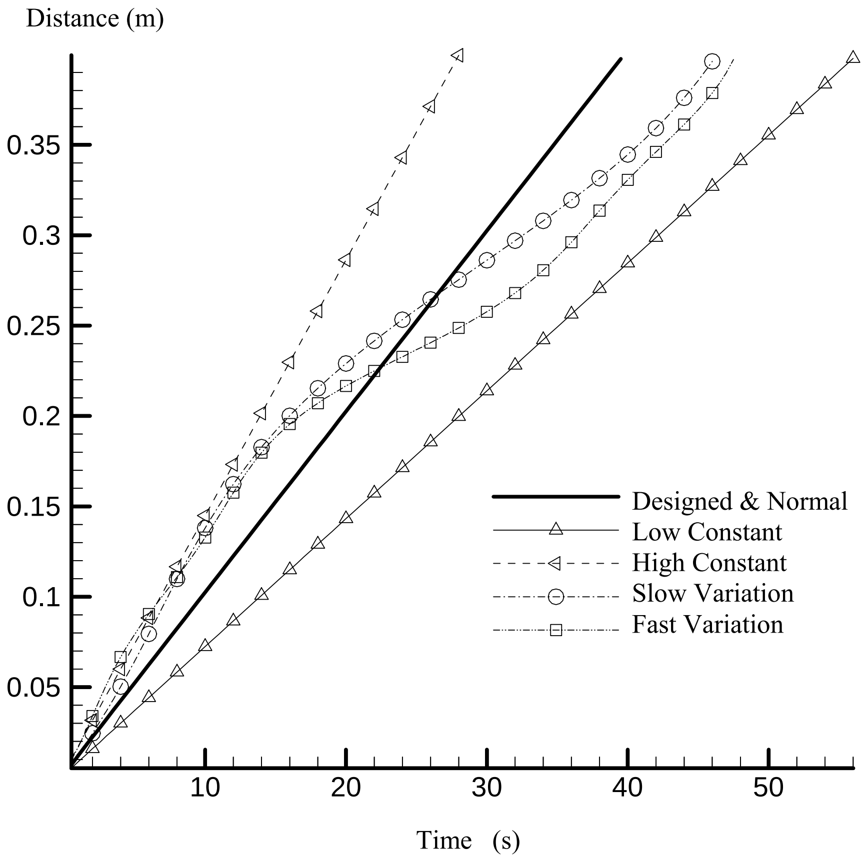

Figure 3. Filling front movement with different permeability distributions.

In order to have a more direct assessment of the control performance, we define a filling front position error e_S as

$$e_S = S - S_{designed} \tag{4}$$

where S is the simulated instant filling front position, $S_{designed}$ is the instant designed filling front position. Obviously, small filling front position error represents better control performance. Figure 3 shows the e_S values under open-loop control. The maximum error, about 16 cm, has been observed at the end of filling process under low constant perform permeability. The maximum error accounts for 40% of the mold length. Errors of more than 10% are also widely observed in other permeability situations, which indicate an unsuccessful open-loop control performance. The inability of the open-loop control requires adaptive control of the filling.

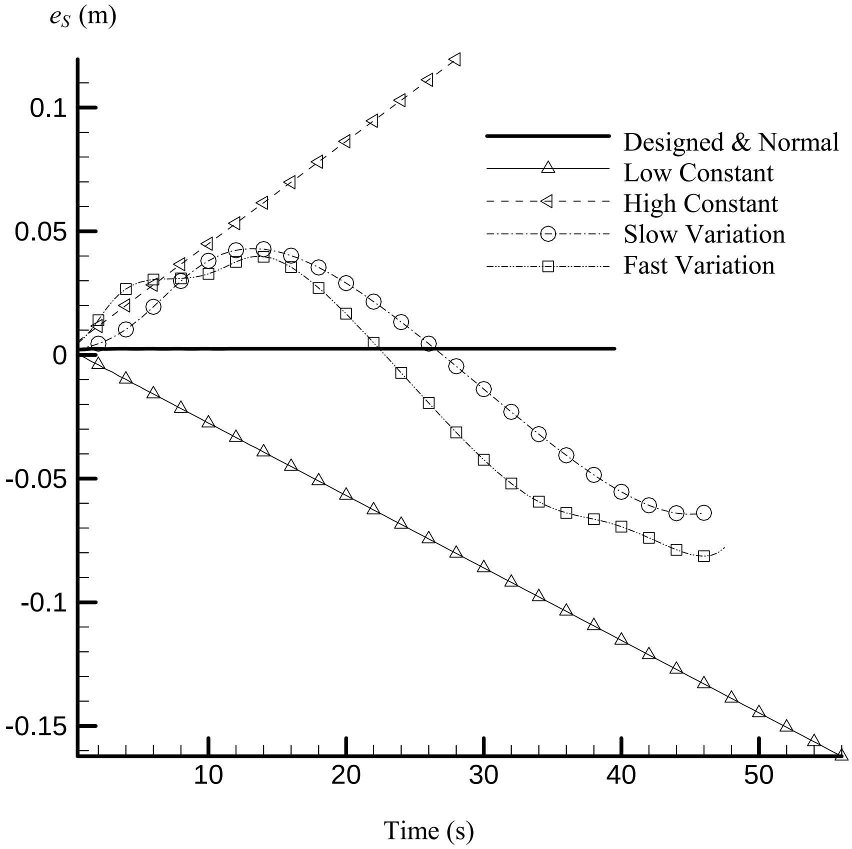

Figure 4. Filling front position error e_S with different permeability distributions with open-loop control.

4. ADAPTIVE CONTROL OF MOLD FILLING

Adaptive control is a special type of closed-loop control system with controllers of non-linear varying parameters. Adaptive technique is more suitable to the control of systems with time-varying parameters [34]. In the problem under consideration in this paper, the controller parameters are updated directly. In this section, direct adaptive control algorithm is devised for the mold filling control.

A designed mold filling process is defined as

$$x_m = f(t) \tag{5}$$

and the corresponding system model is

$$\frac{dx_m}{dt} = \dot{x}_m = -a_m x_m + b_m P_m \tag{6}$$

that is the reference model where *P is* injection pressure and *a* and *b* are system model parameters. Then, the mold filling process can follow the designed one using the following regulator:

$$P(t) = t_0 P_c(t) - S_0 x(t) \tag{7}$$

where t_0 and S_0 are parameters that are updated directly by Lyapunov stability theorem during the filling process as:

$$\begin{aligned} \frac{dS_0}{dt} &= \gamma_1 ex \\ \frac{dt_0}{dt} &= -\gamma_2 eP_c \end{aligned} \tag{8}$$

where γ_1, γ_2 and P_c are constants and *e* is tracking error defined as

$$e = x - x_m \tag{9}$$

We now apply the adaptive control strategies devised above to the mold filling control problem previously attempted by the open-loop control. The parameters in adaptation and control law are chosen in such a way that the control can perform well under a wide range of permeability variations. P_c is chosen about the same value as the gate pressure in the designed situations. Then, parameter γ is adjusted to achieve the control objective. The parameters in direct adaptive control are chosen as follows: $P_c=5.0\times10^5$, Pa, $\gamma_1=8.0\times10^{11}$, $\gamma_2=50$.

During the mold filling under direct adaptive control, the injection pressure is regulated in order for the filling process to follow the designed one. Figure 5 shows the filling front position errors for various permeability situations when time step is 0.5 seconds. The error values decrease as filling progresses. The maximum error occurs at the initial stage of the filling at ~3% of the mold length. The error falls below 1% during most of the filling time and under 0.3% at the end. These results show that in direct adaptive control the actual filling front follows the designed filling front significantly better than open-loop control. Figure 6 shows the corresponding injection pressure with direct adaptive control. This figure shows that the direct controller instantly adjusts the injection pressure during the filling in order to keep filling front moving with the designed constant velocity. The variation in injection pressures depends on the variation in preform permeability. In the cases with constant permeability or low permeability variations, the variation in injection pressures is relatively moderate. However, fast variation in permeability brings more fluctuation in injection pressure due to the relationship between the injection pressure and the permeability.

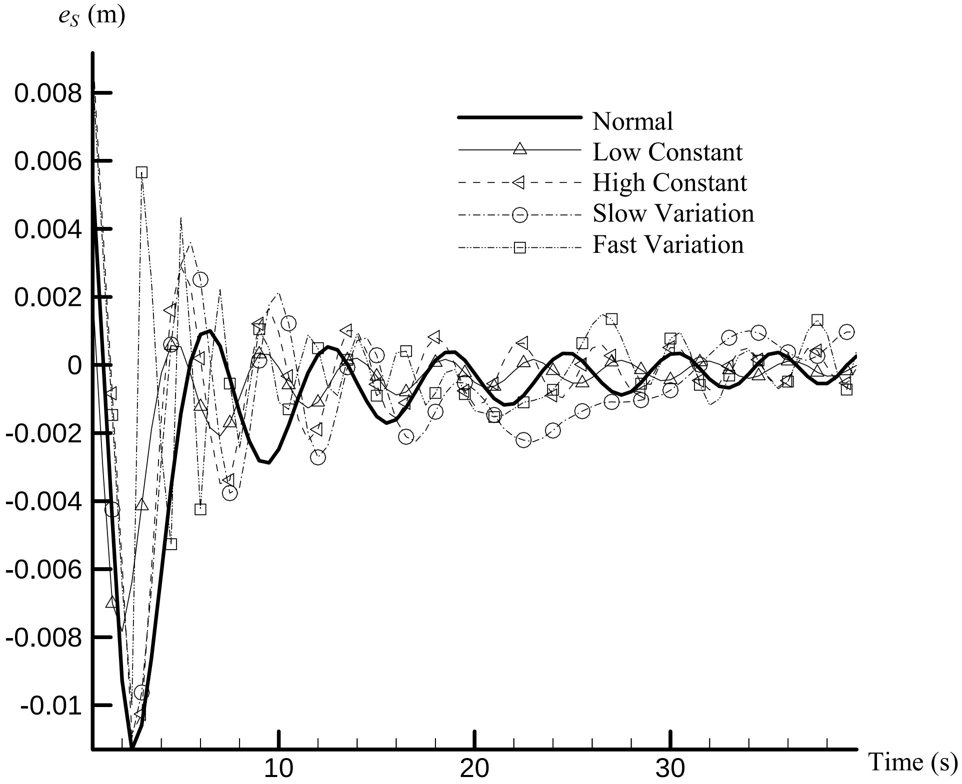

Figure 5. Filling front position error e_S with different permeability distributions with direct adaptive control (time step is 0.5 s).

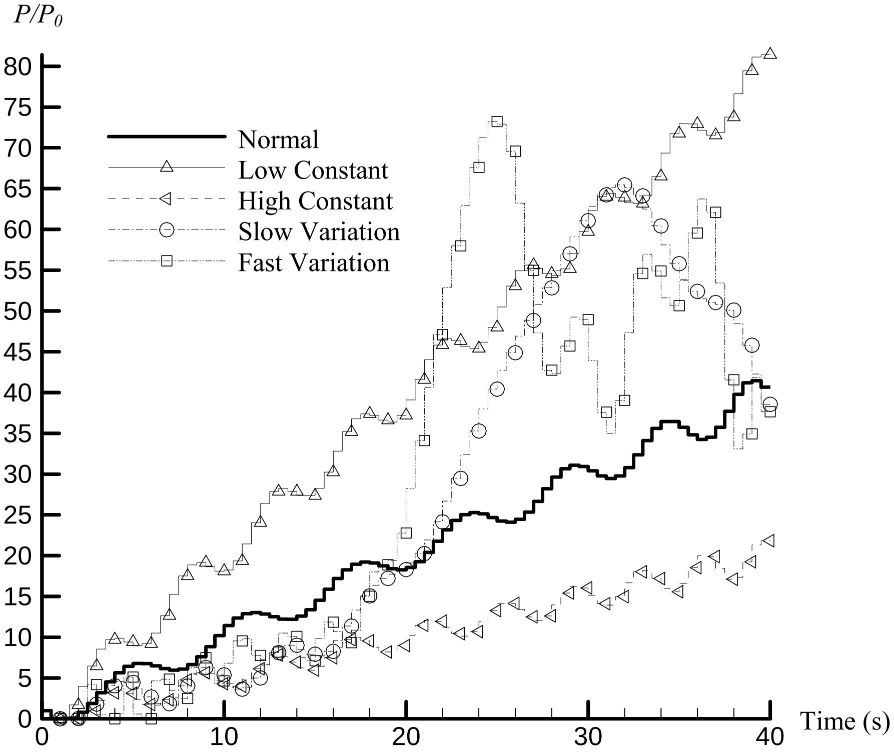

Figure 6. Dimensionless injection pressures with direct control; P_0 is initial injection gate pressure (time step is 0.5 s).

5. CONCLUSIONS

Direct adaptive control strategy for RTM filling has been presented with the objective of achieving consistent mold filling under varying fiber preform permeability values. The control strategy has been evaluated in a RTM filling simulation involving a tube mold. In order to account for the variations in fiber preform permeability that often occur in industrial setting, a wide range of permeability spatial distributions has been considered. Using adaptive control, the actual filling pattern has been successfully controlled to follow the designed filling pattern.

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