Automatic Control of Vacuum Infusion Processes

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Abstract

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Abstract:

This work is a part of a wider research project whose objective is the development of automatic control solutions for vacuum infused processes using artificial vision. Current vacuum infusion processes control solutions are dependent on skilled labour and based on open loop control structure. In addition, they rely solely on valve actuation, which decreases the possibilities for an accurate process control.

The accurate control of the resin flow speed through the fibrous material is crucial for the manufacturing of high quality composite materials. Therefore, an adaptive control solution is proposed to address the non-linear dynamics and the need for a versatile and accurate solution. The controller regulates the resin flow speed by adjusting the pressure difference inside the part mold, using a PI controller with parameters that adapt to the plant dynamics at each time instant.

The proposed solution starts by the identification of an appropriate dynamic model for the system, then the controller is designed and tested in an experimental Vacuum Assisted Resin Transfer Molding laboratory setup.

1. Introduction

This work consists in the design of an automatic control solution for the manufacturing of high quality composite materials in vacuum infused processes, which depends heavily on the accurate regulation of the resin flow speed through dry fibers. This is accomplished by applying an adaptive controller to the pressure difference inside the mold and monitoring the resin flow position through artificial vision.

The development of this control solution is based on an experimental setup located in the facilities of the Institute of Science and Innovation in Mechanical and Industrial Engineering (INEGI), which replicates a Vacuum Assisted Resin Transfer Molding (VA-RTM) process.

The adaptive controller structure consists of a Proportional Integral (PI) controller with time-varying parameters dependent on the evolution of the system dynamics, which is identified online through a Recursive Least Squares (RLS) algorithm.

The work plan consists of:

- Development of a dynamic model structure for the process
- Design the overall control system
- Implementation of the controller in an experimental setup

1.1. Vacuum infusion processes

Vacuum Infusion Processes (VIP) are a subcategory of closed mold processes that distinguish themselves by using vacuum to infuse resin into the laminate. A great advantage of the VIP is the manufacturing of parts with very high fiber content, which reflects positively on its mechanical proprieties. However, it requires detail planning and process design, so the parts can be infused in a reasonable amount of time without any dry spots. Nowadays, the quality of an infusion depends on several factors that are controlled by skilled workers. Therefore, the decisions made by the workers are critical, which makes this process highly dependent on skilled labour.

There is a variant in the vacuum infused processes category called Vacuum Assisted Resin Transfer Molding (VA-RTM). In this process, the fibers are placed inside a rigid mold which has an inlet connected to a resin container and an air outlet connected to a vacuum pump, typically placed on opposite ends of the mold, as seen in Figure 1.

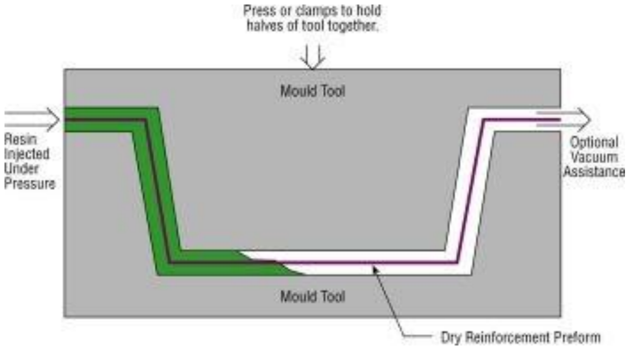

Figure 1 - Vacuum Assisted Resin Transfer Molding [1]

This process allows for better control of the resin flow when compared to a normal vacuum infused process. The rigid mold ensures that the resin only flows through the fibers, whereas the vacuum bag can create resin pockets above the fibers, causing unexpected variances in the resin flow.

1.2. Manufacturing problems

The quality of a part manufactured by VIP is dictated by the amount of resin that penetrates the fibers. A perfect infusion is one where the fibers are completely immersed in resin. The main defects that occur in VIPs are dry spots, micro voids and macro voids. These defects lead to areas in the fibers that do not have hardened resin binding them and therefore have lower mechanical resistance and increased risk of cracking or fracture [2].

Nowadays the VIPs are highly dependent on human supervision. In order to avoid dry spots or voids, the speed of the resin flow is carefully monitored as both high and low flow speeds lead to flawed parts.

The main disadvantages of human supervised VIPs are the costs of skilled labor, the long time spent in each infusion and the high number of parts that are discarded due to flawed infusions. This leads to financial losses and inefficiencies that can be improved using automatic control strategies.

1.3. Control solutions

Some attempts to solve these problems rely on open loop control strategies, where the control action is not related to the system state or any disturbances. These solutions are more common in processes where the system dynamics can be easily calculated and predicted to a certain extent, leading to a model that becomes the basis for the controller design.

The development of open loop control strategies of vacuum infused processes starts with the analysis of the desired geometry and the injection strategy deliberation (i.e. the placement of the resin injectors). The resin infusion is analyzed in a simulation that predicts the formation of dry spots, macro and micro voids. With the simulation results, the injection strategy is tuned, and the formation of defects is minimized. However, despite having a reduced need for parameter adjustment, the presence of a skilled laborer is required to supervise the process in case of an anomaly.

Another approach to this problem is to have feedback on the system state measured by sensors, thus closing the control loop. The use of feedback can overcome disturbances by having the control action based on the error between a reference and the actual system state. As in the open loop approach, the closed loop controllers also require a previous study of the systems dynamics. Despite being more complex, this approach allows for more accurate control solutions [3].

1.4. Previous contributions

This work is part of a research project whose goal is the development of automatic control strategies for vacuum infused processes. It relies on previous contributions by Silva (2016) [4] and Sousa (2017) [5].

Silva (2016) has developed an experimental setup that consists of a rectangular mold with sensors and actuators that allow for the study of vacuum infusions in a controlled environment. The work consists in developing the experimental setup that serves as basis for this project and model its dynamics using a white-box modelling approach. The dynamic model obtained was based on the physical principles involved in the VIP and resulted in the following differential equation:

$$\frac{dx_{ff}}{dt} = \frac{C_r}{x_{ff}} \cdot (\mathrm{P}_e - P_v + a_c) \tag{1}$$

In equation (1), x_{ff} is the resin flow position; P_e and P_v are the pressure at the resin inlet and at the air outlet, respectively; C_r and a_c are variable parameters that correct the non-linearities in the system.

Sousa (2017) developed a pressure control subsystem in the resin container and applied a PI controller to the overall system in a first attempt to control the process. The pressure control was accomplished by regulating the connection of the resin container to a vacuum pump and the ambient air, separately, through a valve action in each connection. This resulted in a controlled subsystem with a significantly faster dynamic behavior than the overall system, which enables the development of active control solutions applied only to the pressure difference and the resin flow position, bypassing the pressure control inside the resin container [5].

1.5. Problem resolution

These previous contributions have found that the speed of the resin flow through the fibers is the factor that most influences the overall quality of the manufacturing process. This premise directed the previous control solutions towards maintaining the resin flow speed at a constant value. It has also been found that the resin flow speed is highly influenced by the pressure difference between the resin container and the vacuum at the air outlet [4] [5].

The vacuum infusion processes are difficult to model and control due to the unpredictability of the system dynamics. It varies with factors that cannot be controlled, and has a time variant behavior throughout the infusion.

This work proposes to solve this problem by implementing an adaptive PI controller to the pressure in the resin container, which identifies the system dynamics online and adjusts the parameters of a PI controller accordingly.

2. Experimental setup

A considerable part of this work relies on the analysis of experimental data obtained from an experimental setup of a Vacuum-Assisted Resin Transfer Molding process that has been specifically designed for this project. Its main purpose is to provide a controlled environment to minimize the influence of unpredictable or uncontrollable factors. It is of most importance to ensure that all experiments are performed under similar conditions so that they can be compared [4].

The setup is composed mainly by the following parts:

- Acrylic mold
- Vacuum pump
- Resin container
- Pressure sensors
- Valves
- Camera

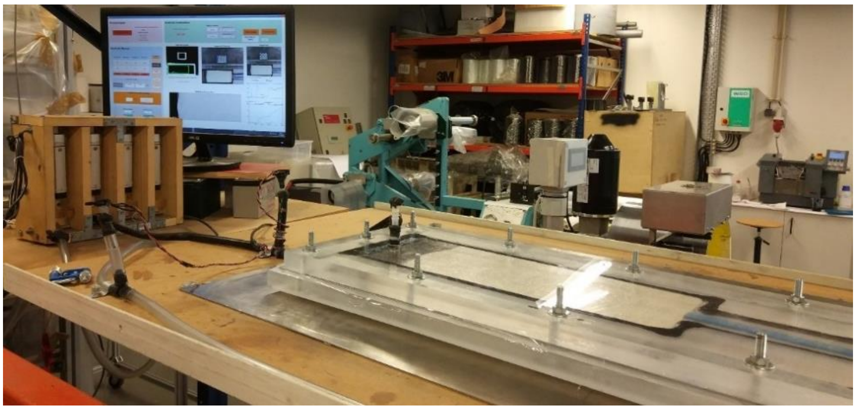

Figure 2 - Experimental setup

The experimental setup (Figure 2) assembly is depicted in the Simulink block diagram presented in Figure 3:

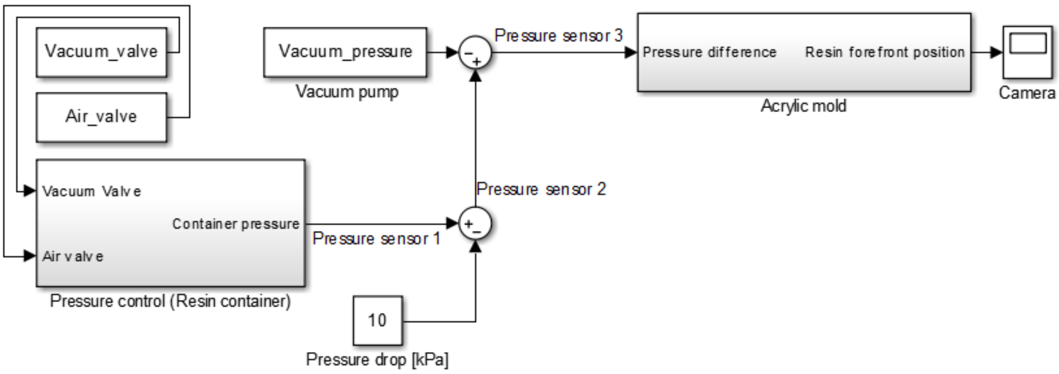

Figure 3 - Simulink block diagram of the experimental setup

The resin forefront position is measured by a common webcam placed above the acrylic mold. The position is influenced mainly by the pressure difference between the mold inlet (connected to a resin container) and its outlet (connected to a vacuum pump). The resin container has its own pressure control subsystem (Figure 4) that adjusts the pressure at the resin inlet by regulating the state of two valves, connected to the vacuum pump and the ambient air, separately.

Figure 4 - schematic representation of the pressure control subsystem [5]

3. System identification

This chapter presents the development of a dynamic model that accurately describes the system dynamics.

The system identification resulted in a dynamic model with three main characteristics:

- first order integrator dynamic behavior
- time-variant parameters
- dependent on external factors

Despite not having reached a parametric model that fits all the experimental data, the model structure is adequate to describe the VA-RTM process general behavior and serves as basis for a control solution. Its open loop transfer function is described in equation (2):

$$\hat{G}(s) = \frac{1}{T(x) \cdot s} \qquad ; \qquad T(x) = C \cdot x \tag{2}$$

The data analyzed in this section results from infusions performed in the experimental setup described in chapter 2. For each infusion the most important collected data is the Resin forefront position and the Pressure difference between the resin inlet and the air outlet.

The first sets of experimental data to be considered are three infusions with a response to a constant pressure difference input:

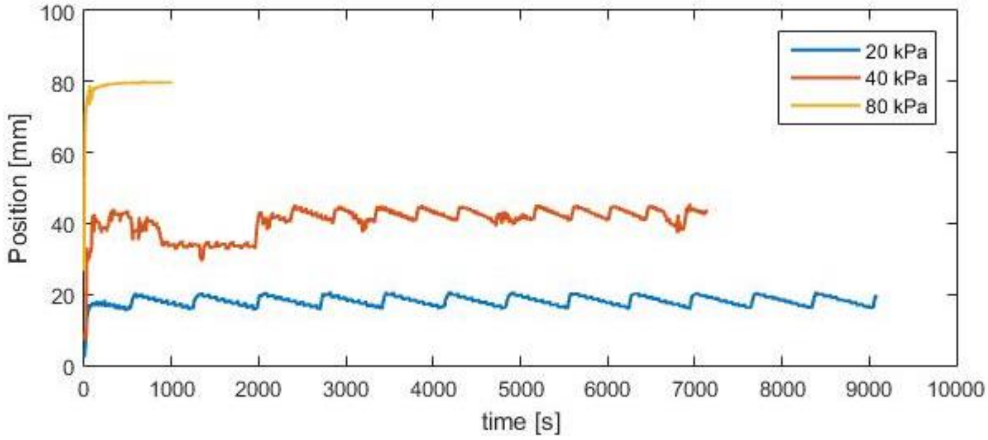

Figure 5 - Pressure difference: Constant inputs

The pressure difference remains constant throughout each infusion, at approximately 20 kPa, 40 kPa and 80 kPa. Although a small variance at the input can be observed (Figure 5 and Figure 6), it has no considerable influence in the resin flow and it only happens due to the vacuum pump bang-bang controller.

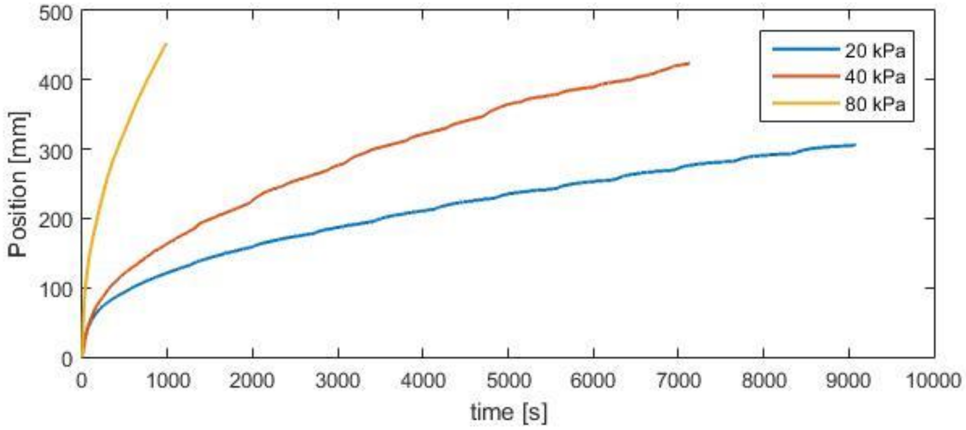

Figure 6 - Forefront position: Response to constant inputs

With a relatively constant input, the resin forefront position increases through the whole experiments (Figure 6), which leads to the hypothesis that the system presents a first-order integrator dynamics.

The three experiments presented earlier are combined into a piecewise linearized model to better understand their joint dynamics:

This linearization representation (Figure 7) show that the system dynamics are time-variant. The forefront position increases according to the pressure difference, but its growth rate decreases with the advance of the resin flow, as confirmed in Figure 7:

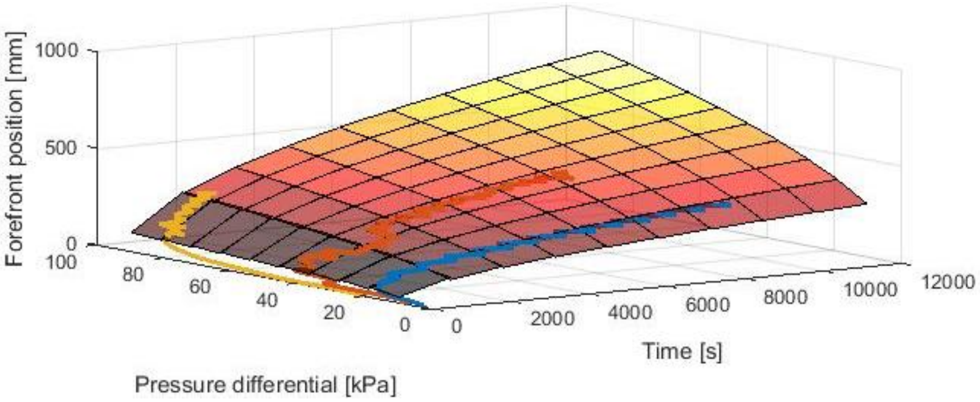

Figure 7 - Piecewise linearization

Considering the continuous increase with a constant input and the time-variant growth rate, the following model structure is assumed:

$$\hat{G}(s) = \frac{1}{T(x) \cdot s} \qquad ; \qquad T(x) = C \cdot x \tag{3}$$

Here, the estimated transfer function consists of an integrator with a proportional component that varies in inverse proportion with the resin forefront position, x, in mm and a coefficient of proportionality C. The function $T(x)$ represents the time-variant behavior present in the system.

The proposed model response is compared to the experimental data and its parameters are adjusted to better fit the system response by minimizing the Mean Squared Error (MSE):

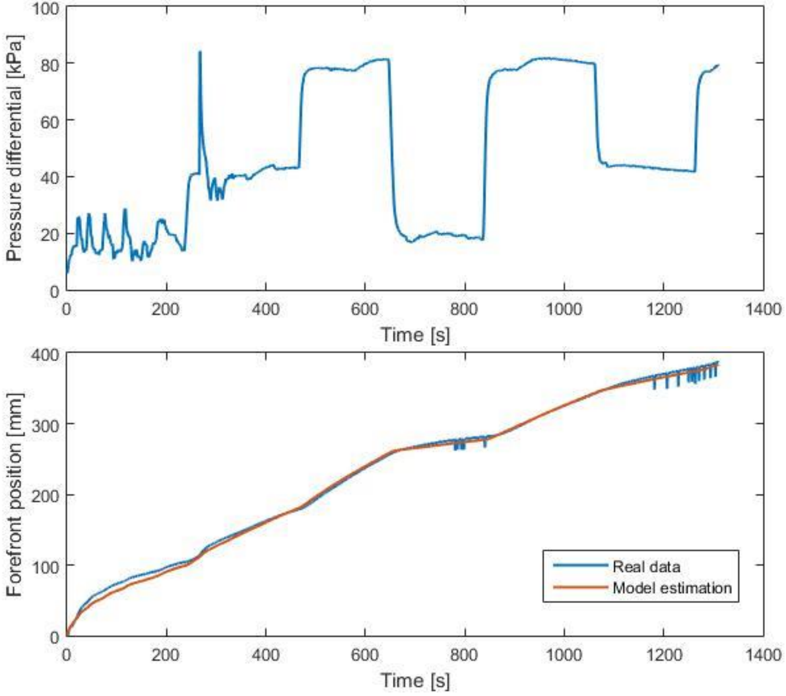

Figure 8 - Experiment 1

The minimum MSE obtained for the infusion shown in Figure 8 is 20.11, which resulted from a parameter C of 0.82. The estimated open loop transfer function applied to this infusion is:

$$\hat{G}_{OL}(s) = \frac{1}{0.82\, x \cdot s} \tag{4}$$

The validity of the proposed model is evaluated by comparing the responses of the model and the real system to the same input. The model is applied to 5 infusions and adjusted to each infusion by computing the parameter C that minimizes the mean square error. This analysis lead to the results presented in Table 1:

	PARAMETER C	**MEAN SQUARED ERROR**
EXPERIMENT 1	0.82	20.1
EXPERIMENT 2	1.41	48.6
EXPERIMENT 3	0.66	33.7
EXPERIMENT 4	0.93	51.2
EXPERIMENT 5	0.86	2.1

Table 1 – Model parameter C estimation results

Table 1 shows the parameter C and the mean squared error of a model adjustment to its corresponding experiment. The structural hypothesis proposed earlier provides models that fit the experimental data with a low MSE. However, the parameter C varies from 0.66 to 1.41 which indicates that the repeatability of the experiments is compromised and beyond the reach of this experimental setup. This inconsistency proves the need for an adaptive controller, which is the main object of this work.

4. Controller design

The controller design for the VA-RTM process experimental setup consists of an adaptive control structure that estimates the system parameters online through a Recursive Least Squares Estimator (RLSE), which are applied in the adjustment of a PI controller parameters.

The controller aims to regulate the resin forefront position by comparing it to a ramp shaped reference and using the error between them as a basis to correct it. As there is some degree of uncertainty in the calculation of parameter C, the controller must adapt to the changes in the plant dynamics.

An adaptive controller is one that adjusts its parameters to a dynamic model identified online. A typical adaptive controller structure can be seen in Figure 9 with two main components: the estimator and the controller [6].

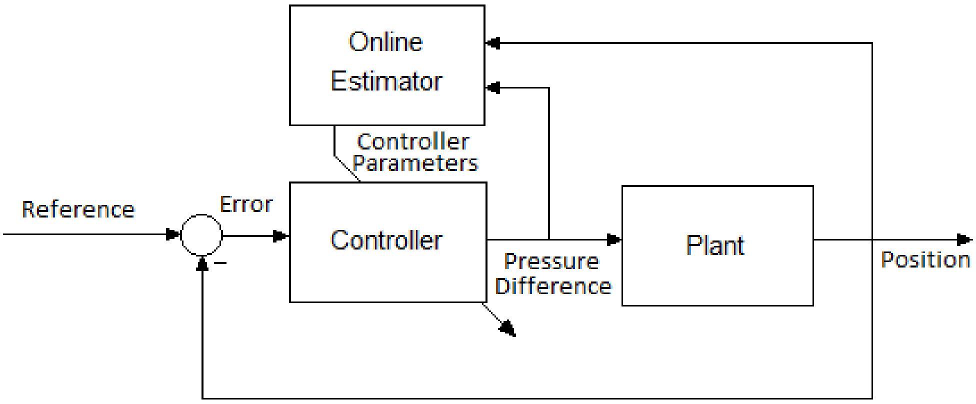

Figure 9 - Adaptive controller structure

4.1. Controller details

The adaptive PI controller parameters, K_P and K_I, vary according to the estimated dynamics to ensure that the system response behaves as designed. Also, due to the presence of saturation in the control action, a reset wind-up feature is implemented to the controller, thus avoiding the integral error accumulation outside the saturation limits, according to Figure 10.

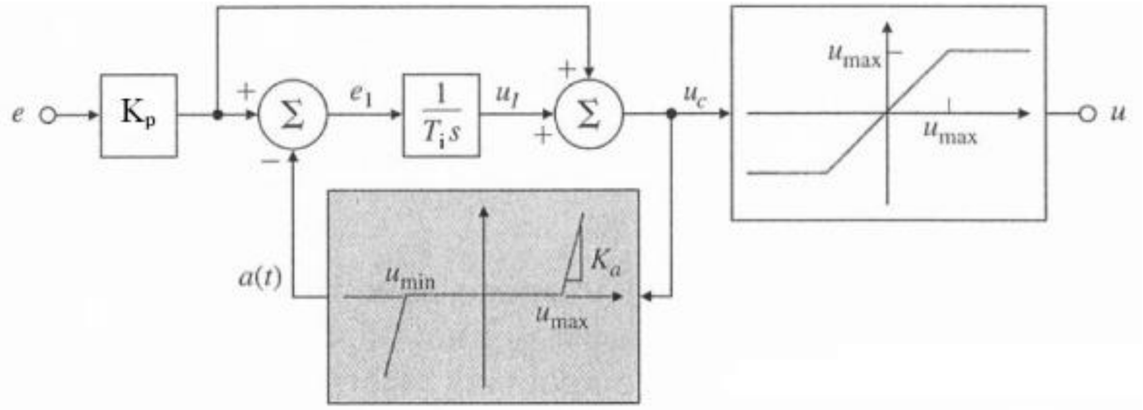

Figure 10 - Anti-windup

The RLSE returns two parameters θ_1 and θ_2, that are associated to each regressor from Figure 11, one of the estimated parameters is the sampling time, T_0 and the other is the desired parameter T.

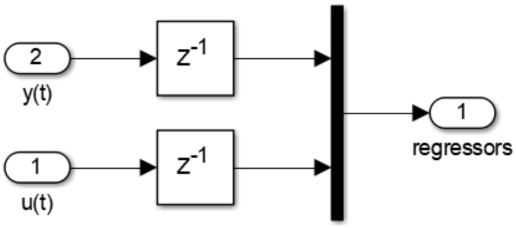

Figure 11 - Regressors selection in *Simulink*

The *PID tuner* tool calculations result in gains that relate the estimated parameter T and the controller parameters, which are 0.6 for K_I and 0.03 for K_P. However, the tuning performed in simulation lead to improved controller parameters that are better suited for its real-world application: 0.3 for K_I and 0.005 for K_P, as shown in Figure 12.

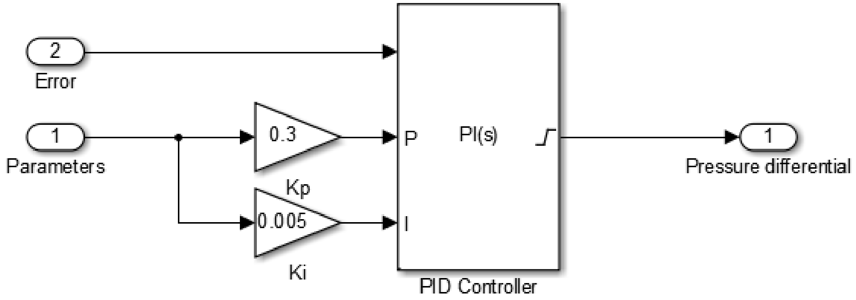

Figure 12 - Simulation controller

5. Experimental results

This chapter presents the experimental results of the adaptive controller developed throughout this work.

The most important data sets to consider and analyze are:

- The control action imposed in the mold
- The resin flow position evolution compared to the reference
- The error between the reference and the resin forefront position

5.1. Infusion details

When applying the adaptive controller to the experimental setup, there are a few details that need to be taken under consideration, especially at the beginning of the infusion.

As the resin flow is controlled through the pressure inside the resin container, the feeding tube must be free of air pockets. Otherwise the control action does not affect the resin flow in a consistent way due to the compression of the remaining air inside the tube. Also, if the control action is applied before the resin reaches the region of interest captured by the camera, the error between the forefront position and the reference increases significantly before the infusion begins, which leads to an undesired overshoot as the controller tries to compensate for an increasing positional error that does not represent a true error.

To overcome these issues, an alternative control action is implemented for the transient region. This transient controller sets the pressure difference at 20 kPa until the resin forefront reaches 20 mm, at which point the adaptive controller is applied as well as the ramp shaped reference. Although this compromises the first 20 mm of the infusion, it prevents both the air pockets and the overshooting.

Another detail that has to be taken into account is the influence of the controller saturation. The maximum pressure that can be applied to the resin container is the atmospheric pressure, at 100 kPa. When taking into consideration the pressure drop from the container to the mold, it is clear that the experimental setup is unable to impose a pressure difference greater than 80 kPa, as the vacuum pressure remains close to 10 kPa.

5.2. Controlled infusion

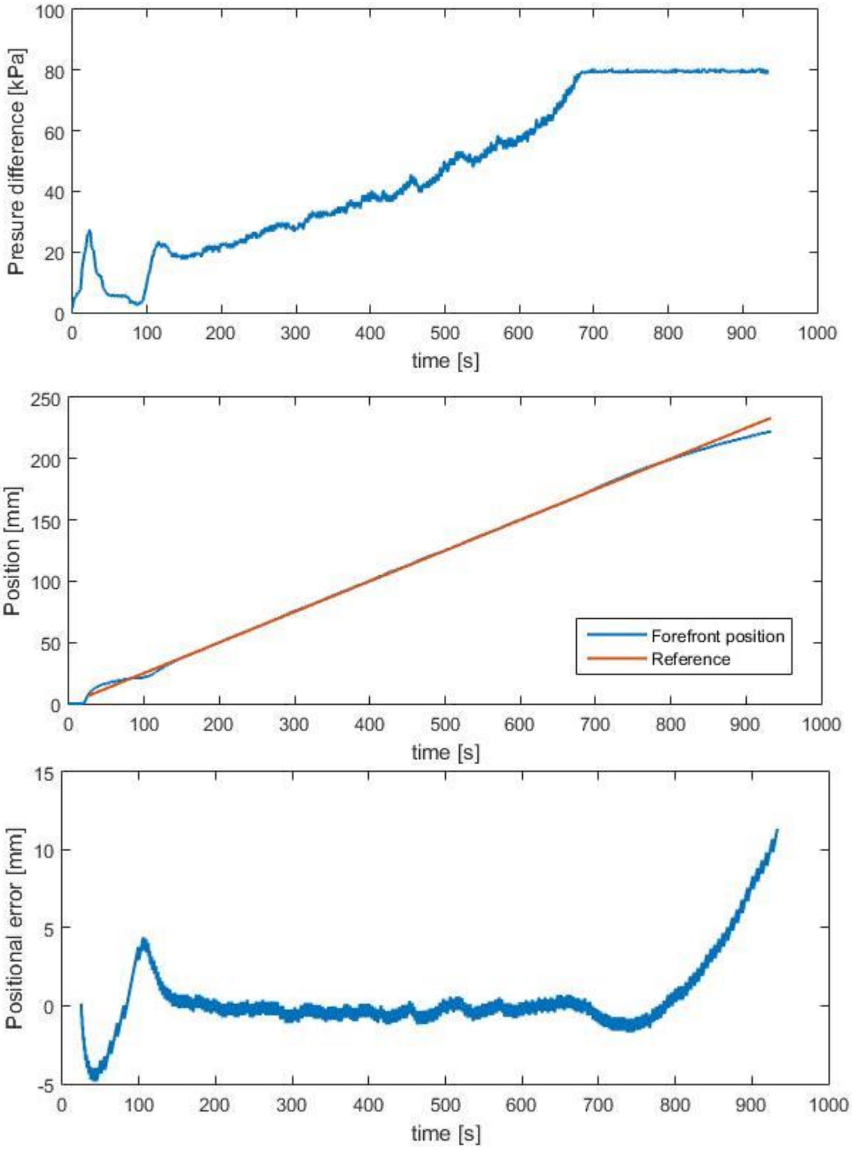

Figure 13 - Controlled infusion 2

The infusion presented in Figure 13 shows very low oscillation in the control action. The positional error settles below 2 mm after 124 seconds, at 29 mm, which shows a successful control of the resin flow. The system saturates at 685 seconds when the position is at 170 mm, however, the error only exceeds the 2 mm limit at 824 seconds, which occurs at 204 mm.

6. Conclusions

This work provides a successful control strategy for the resin flow speed control in VA-RTM processes.

The development of this control solution resulted from the identification of the system dynamic model, the design of an adaptive controller and its application to an experimental setup.

The dynamic modelling of this process showed a time-variant behavior and lack of consistency between experiments. The time-variant behavior is overcome by adjusting the model dynamics to the progression of the resin flow. The discrepancies between infusions are not possible to work around, as the process dynamics vary according to factors outside the reach of this experimental setup.

The control solution developed for this process is an adaptive controller. It is based on a PI controller structure with parameters that adjust to the online identified process dynamics, which is achieved through a recursive least squares estimator.

The controller is successfully applied to the experimental setup with all the adjustments it requires, such as transient control and parameter tuning. The real-world results show a controlled resin forefront position that settles within a 2 mm range of its reference before it reaches 10% of the part full length, 400 mm.

7. References

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