

Design of a Plastic Extrusion System Controller

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Abstract—Most polymer processing industries nowadays employ plastic extrusion as a highly efficient and reliable method. In a plastic extrusion system, the output variables are the outflow from the die, the polymer pressure and temperature. Acceptable output variables cannot be achieved without an effective control of the process. The main controlling variable is the screw speed in relation with the pressure and the temperature. The screw requires a high degree of speed accuracy in order to ensure the best performance of the process. Unfortunately, in many industrial processes involving plastic extrusion, inadequate control of the screw speed, the pressure, and the temperature has resulted in a poor performance of the overall system. This research deals with the modeling and control of an overall plastic extrusion system. A suitable digital compensator or controller has been designed using the MATLAB software, to improve the screw speed and the pressure of single screw plastic extruder. The compensator $D(z)$ ensures an optimum control of the plastic extrusion process with 5.11percent overshoot, 6.66 seconds settling time and a rise time of 1.96 seconds to a unit step input.

Keywords— Digital Compensator, Extruder, Plastic Extrusion, Single Screw Extruder

1 INTRODUCTION

Polymers are used with increasing frequency in many industrial fields such as food, electronics, automobiles manufacture and repair. Plastics are typically polymers of high molecular weight, and may contain other substances to improve performance and/or reduce cost [3]. In 1995, plastics production in the world was about 100 million tons [5]. Thus, it is necessary to develop technologies that improve polymer properties and increase polymer production. Originally, polymer properties were controlled by selection of appropriate monomers [3]. The diverse use of today's plastics requires more stringent quality specifications, which are difficult to achieve with individual base polymers [4]. Polymer extrusion is a major compounding process used in the plastics industry for the continuous production tubing, pipe, film, sheet, coated wire, and other polymer products [6].

An extruder is a plastics manufacturing unit operation that is used to produce thermoplastic polymers with a uniform cross section, such as pipe, hose, sheet, film and profiles. Since extruders also produce the polymer pellets that are used by other polymer processing operations (such as film blowing, injection moulding and blow moulding). For instance, a single screw extruder consists of an auger-like rotating screw that closely fits within a heated barrel. Extruders can be fed with solid plastic pellets, chips, beads or powder. The functions of produce an extruder are to convey the solid polymer from the hopper, compact and melt the pellets, mix the resulting highly viscous polymer melt, pressurize and pump it through a die that produces the shape of the plastic product. In the polymer extrusion process, suitable raw material is pushed across a metal die to produce a melt in a desired shape [8]. Several unit operations can be performed in a single machine, including mixing, heating, kneading, shearing, reaction, and shaping [3]. The overall goal of extrusion is to produce a well-mixed polymer melt at the proper conditions of flow rate, pressure and temperature for the next polymer processing operation, which usually forms the polymer melt into a solid product [2]. The main controlling variable in a single screw extruder is the speed, since the response of the process to it is rapid [7].

Additives such as colorants and UV inhibitors (in either liq-

uid or pellet form) are often used and can be mixed into the resin prior to arriving at the hopper. The process has much in common with plastic injection moulding from the point of the extruder technology though it differs in that it is usually a continuous process [7].

The first precursors to the modern extruder were developed in the early 19th century. In 1820, Thomas Hancock invented a rubber "masticator" designed to reclaim processed rubber scraps, and in 1836 Edwin Chaffee developed a two-roller machine to mix additives into rubber. The first thermoplastic extrusion was in 1935 by Paul Troester and his wife Ashley Gershoff in Hamburg, Germany. Shortly after, Roberto Colombo of LMP developed the first twin screw extruders in Italy [9].

2 SINGLE SCREW PLASTIC EXTRUDER MODEL

A single screw extruder, the most widely used type, is employed in this lab [2]. The diagram of typical single screw plastic/polymer extruder is shown in Fig. 1.

The extruder output flow is a function of the screw speed, plastic viscosity, screw leakage, pressure build-up, and so on. Assuming an uninterrupted resin supply and negligible screw overflight leakage, a relationship exist between the production rate (or screw speed) of the extruder, and the pressure [1]. From the typical single screw plastic/polymer extruder shown in Figures 1, a mathematical model of plastic polymer for single screw extruder in terms of the screw speed and the pressure can be derived as follows:

$$Q = \alpha N - \beta \left(\frac{d^2 P}{dt^2} \right) \quad (1)$$

Where,

Q = Volumetric flow rate of polymer (m³/s), N = Extruder Screw Speed (rpm), P = Pressure of polymer along the Extruder (Pa), μ = Polymer melt viscosity (Pas), α = Drag flow coefficient (m³), β = Pressure flow coefficient (m³). The flow rate of liquid plastic in the plastic extruder as a function of the

pressure increase and the extruder screw speed can be described by (1).

$$Q = \frac{dP}{dt} + \alpha P \tag{2}$$

Combining (1) and (2), yields

$$\frac{dP}{dt} + \alpha P = \alpha N - \beta \left(\frac{d^2 P}{dt^2} \right) \tag{3}$$

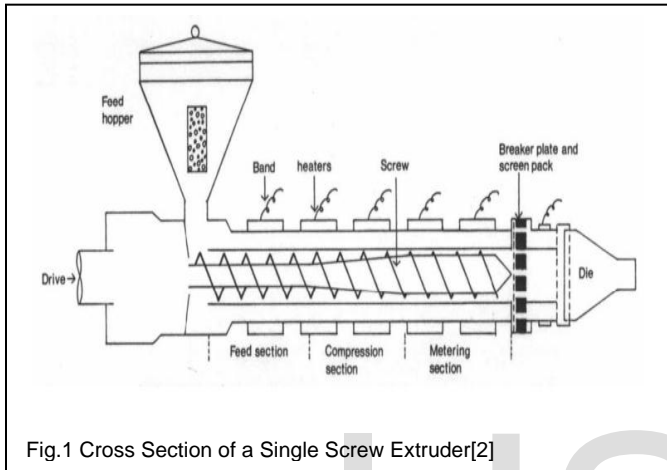


Fig.1 Cross Section of a Single Screw Extruder[2]

Rearranging (3), yields

$$\beta \frac{d^2 P}{dt^2} + \mu \frac{dP}{dt} + \mu \alpha P = \alpha \mu N \tag{4}$$

The Laplace Transform of (4) yields

$$P(s)(\beta s^2 + \mu s + \mu \alpha) = \alpha \mu N(s) \tag{5}$$

Therefore, the Transfer Function of the system $G_p(s)$ obtained from (5) is

$$G_p(s) = \frac{P(s)}{N(s)} = \frac{\alpha \mu}{\beta s^2 + \mu s + \alpha \beta} \tag{6}$$

In [2] it was stated that α and β are geometric factors that are constant for a given screw/barrel combination. For typical Single Screw Plastic Extrusion System, the Polymer melt viscosity $\mu = 325 \text{ Pa s}$, Drag flow coefficient $\alpha = 0.13601 \text{ m}^3$, Pressure flow coefficient $\beta = 498.75 \text{ m}^3$. Putting these values into Equation (5), the actual Transfer Function of the system is obtained in Equation (7).

$$G_p(s) = \frac{44.23}{s^2 + 0.65s + 0.136} \tag{7}$$

The block digram representing a closed-loop Single Screw Plastic Extrusion system with $G_p(s)$ and a unity feedback is shown in Fig. 2.

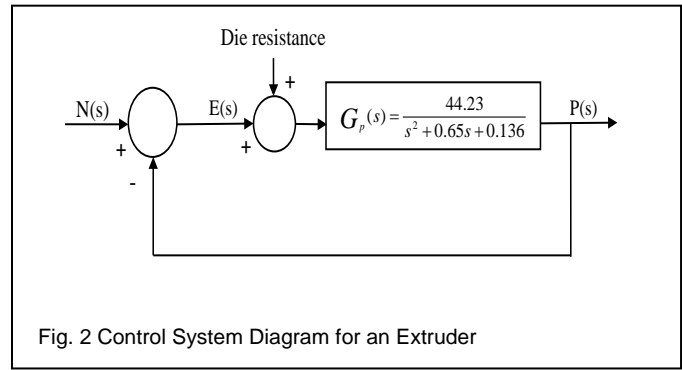


Fig. 2 Control System Diagram for an Extruder

3 DESIGN OBJECTIVES

The design goal in the control system shown in Fig.2 is to design a compensator $D(z)$ that will ensure a unit step settling time of less than 2 seconds using MATLAB. Appropriate values of the compensator that will ensure unit step settling time of less than 2 seconds can be achieved by tuning the entire system automatically using MATLAB control toolbox. The root locus tool of the toolbox is specifically used to confirm the obtained values of $D(z)$.

3.1 Design Specification

- (a) Percentage overshoot less than 5.50% to a unit step input.
- (b) Settling time less than 7.0 seconds to a unit step input.
- (c) Rise time of less than 5.0 seconds to a unit step input.

The first approach is to determine the response of the original system to a step input. The following MATLAB code helps to achieve that.

For open-loop transfer function we have:

```
num=44.23;
den=[1 0.65 0.136];
Gp=tf(num,den)
Transfer function:
```

44.2

$$s^2 + 0.65 s + 0.136$$

Continuous-time zero/pole/gain model

NOTE: $G_p = G_p(s)$, the open-loop transfer function and $G_s = G(s)$ which is the closed-loop transfer function. The open-loop transfer function is the same as in (7).

The MATLAB code for closed-loop transfer function with unity feedback is given as follows:

```
Cloop = feedback(Gp,1).
```

Transfer function:

44.23

$$s^2 + 0.65 s + 44.37$$

Continuous-time zero/pole/gain model

Hence, the closed-loop transfer function of the uncompensated system is given as:

$$G(s) = \frac{44.23}{s^2 + 0.65s + 44.37} \tag{8}$$

The step response of $G(s)$ is given in MATLAB as Step (Gs) and is shown in Fig. 3

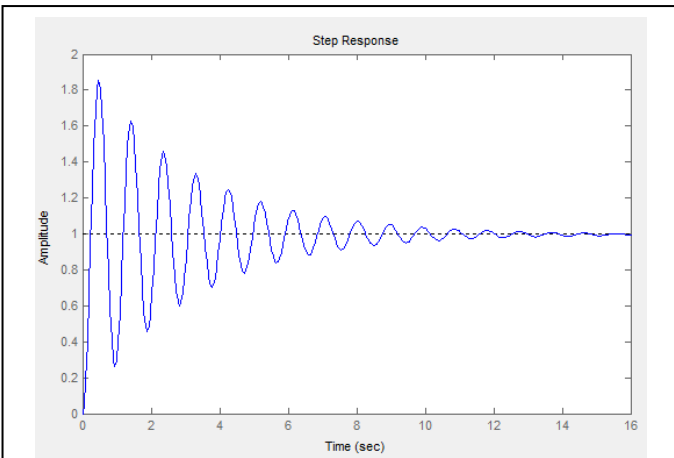


Fig.3 Unit Step Response for $G(s)$

Fig.3 shows a unit step response for the uncompensated system with an overshoot of 85.8%, settling time of 11.9s, and a rise time of 0.162s. To ensure the stability of the system, a suitable compensator will be introduced into the system by tuning with MATLAB control system toolbox. The block diagram of the control system with $G_c(s)$ is shown in Fig. 4.

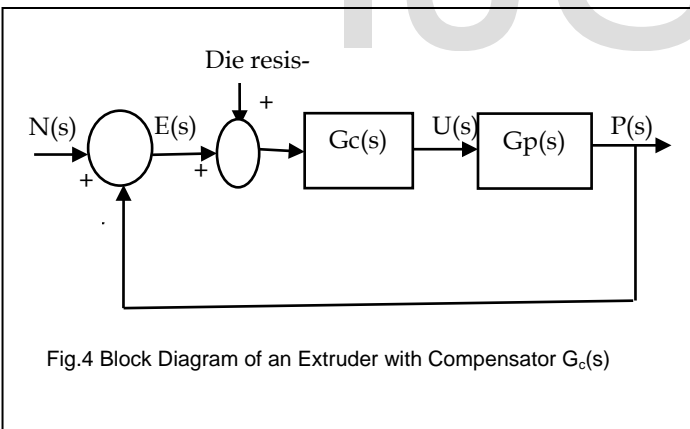


Fig.4 Block Diagram of an Extruder with Compensator $G_c(s)$

The result of the tuning of Single Screw Plastic Extrusion control system with open-loop Transfer Function $G_p(s)$ using the Root Locus plot of the MATLAB control system toolbox is as shown in Fig.5. From the MATLAB tuned diagram in Fig. 5, a suitable compensator for a single screw plastic extrusion of the form given in (9) is obtained.

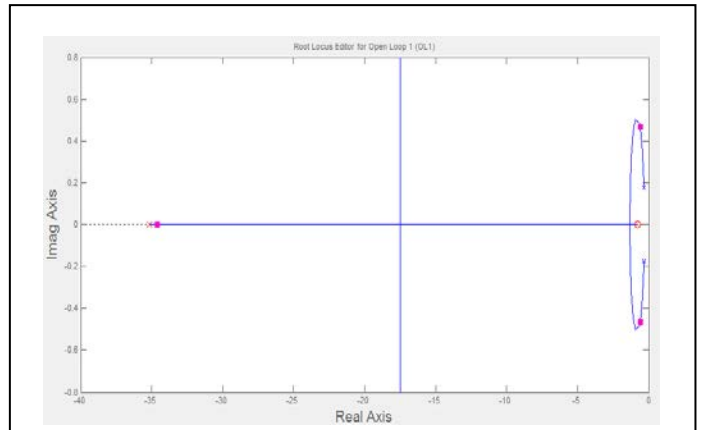


Fig. 5 The Root Locus plot of the tuned system

$$G_c(s) = K \frac{(s+a)}{s+b} \tag{9}$$

where, K is the gain, a is the zero of compensator, and b is the pole of the compensator. $K= 0.419$, $a= 0.801$, $b= 35.2$. Substituting these values into equation (9) yields:

$$G_c(s) = 0.419 \frac{(s+0.801)}{s+35.2} \tag{10}$$

The step response of the compensated system in continuous time is shown in Fig. 6.

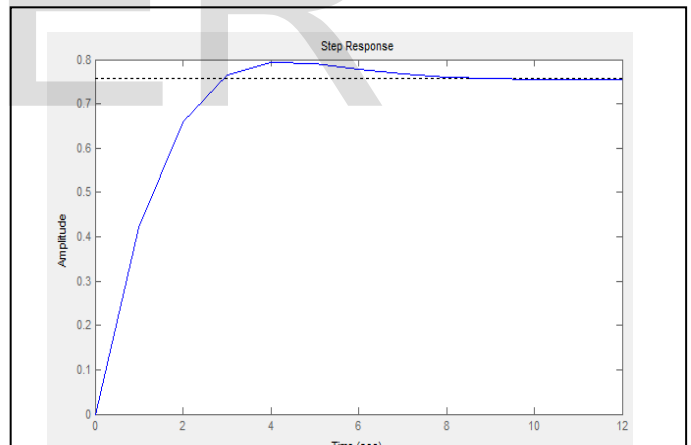


Fig. 6 Unit Step Response of the Compensated System in Continuous time

Fig. 6 shows the unit Step Response for the single screw plastic extrusion control system when a compensator $G_c(s)$ is added to it. The overshoot is 4.92%, settling time is 6.7s, and rise time is 2.02s for the compensated system.

4 DIGITAL COMPENSATOR DESIGN

A Digital Compensator $D(z)$ of the form in (11) can now be derived from (10) using the Tustin rule. It states that:

$$s = \frac{2(z-1)}{T(z+1)},$$

Where T=0.01s

$$D(z) = C \frac{(z-A)}{z-B} \quad (11)$$

$$D(z) = 0.419 \frac{\left(\frac{2(z-1)}{T(z+1)}\right) + 0.801}{\left(\frac{2(z-1)}{T(z+1)}\right) + 35.2} = \frac{0.35772(z-0.992)}{(z-0.700)} \quad (12)$$

Equation (12) is the digital controller designed for the system. The closed loop transfer function of the system in z domain is given by

$$G(z) = \frac{0.00078938(z+0.9978)(z-0.992)}{(z-7052)(z^2-1.9882+0.9882)} \quad (13)$$

Fig. 7 shows the step response of the compensated system in discrete time.

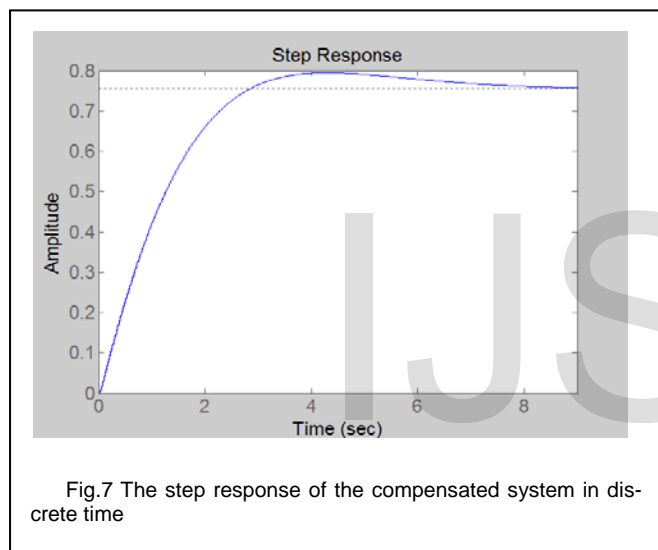


Fig.7 The step response of the compensated system in discrete time

In Fig.7, the overshoot of the system is 5.11%, the settling time is 6.66s and the rise time is 1.96s.

4 CONCLUSION

The design specifications were given in continuous time domain and it was desired to design a digital controller that will make the system attain a settling time of 2seconds and meet the stated specifications. To achieve this, the MATLAB control system tool box was used to select the compensator pole and zero and by graphical tuning of the Root Locus plot, an appreciable gain was obtained for the compensator Gc(s) which yield the controller that meets the design specifications in continuous time domain. Gc(s) was later converted to D(z) in discrete time domain to represent the digital controller. The overshoot of the response in discrete time is slightly greater than that of the continuous time. This is due to the error in the conversion scale used.

The advantage of this controller is that it gives an optimal performance for the plastic extrusion system. This is obvious from the fact that the response of the uncompensated system shows high degree of instability whose effect was taken care of by the controller.

Though the conventional controller designed for the system was able to meet the design specifications and provides appreciable performance characteristics for the system; future work aims at using a more robust and intelligent control technique that will yield better performance.

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