

Control System Design for a Continuous Gravimetric Blender

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Abstract – In this work the control system for a continuous gravimetric blender for polymer extrusion process has been designed. The plant considered in this paper is a blending machine that mixes two different polymers, a bulk one and an additive. Each component of the mix is metered by a dedicated screw meter system. The mass delivered by each meter is measured by a load cell. The two components are poured into a hopper (the mixer) directly embedded on the extruder input. The control objectives are manifold and include: accurate mass flow estimate on the basis of the weight and screw speed measurements; accurate mass flow regulation of each meter; keeping of the relative proportions among all the components that are metered in all the operating conditions; guarantee that inside the mixer there is always material enough to fulfill the mass flow variation request of the extruder.

Keywords: Cascade control, plastic extrusion process, plastic metering.

1. INTRODUCTION

Continuous gravimetric blenders are key elements in the plastic extrusion process, which has a standard setup including a feeding section, a barrel and a head with a die for shaping [5,6,10]. In the feeding section, the solid polymer is fed into the extruder through a blender in the form of granulate, pellets or irregular small bits. Usually, from two to six different polymeric components are blended in the feeding section by means of gravimetric or volumetric systems. Then, the polymer is transported along the barrel by means of a rotating screw. The barrel wall is equipped with a number of electric heaters which melt the polymer. The material is melted and pushed towards the die where the extruded final product is shaped and expelled. During the process, the polymer undergoes very complex thermo-mechanical transformations inducing strong changes in the physical properties of the material [7,11,15]. However the final product quality in extrusion is essentially characterized by a precisely-regulated volumetric flow of the polymer through the extruder [3,4,12,14,15,17]. This can be achieved by fine regulation of the mass flow delivered from the blender to the extruder.

Traditionally, continuous metering of plastic was performed by volumetric blenders, which are not equipped to measure the plastic quantity actually delivered to the extruder. So, they are controlled in open loop and their performances are limited. Recently, a new generation of plastic blenders for extrusion has been conceived, which are equipped with load

cell to measure the plastic weight fed into the extruder. So, gravimetric blenders can provide accurate flow control by means of closed loop control [9]: they can give the chance of a considerable increase in performances, provided that an accurate mass flow estimate is computed on the basis of the weight measurements. In fact, in metering process, accuracy is an essential requirement in particular for additive components which are metered at very low flow values. Closed loop control of gravimetric blending provides many advantages with respect to volumetric blenders: metering is independent of material density variations; the frequent calibrations needed for volumetric feeders are not necessary; the increased accuracy considerably reduces the incidence of raw material costs, since each component is metered without any waste.

In this paper, the control system design problem for a continuous gravimetric blender for two polymeric granulates is considered. Specifically, a cascade control architecture has been used, due to the peculiar structure of the plant used for the tests. The inner loop is devoted to the regulation of the mass flow of the primary meters, one for each plastic components. This control system has been designed on the basis of an estimate of the mass flow obtained by joint use of Kalman Filter and numerical differentiation. Also, the control algorithm has been designed so that the ratios among the components defined in the recipe are kept in every operating condition. The outer loop has been designed in order to keep a constant mass of plastic in the hopper directly connected to the extruder, despite of its flow variation requests.

The paper is organized as follows. In Section II, the experimental equipment is illustrated and the control problems are defined. In Section III, the control algorithm for the primary meter is described together with the algorithm for mass flow estimation. In Section IV the mixer control loop is described. Section V is devoted to concluding remarks.

2. EXPERIMENTAL SETUP AND PROBLEM STATEMENT

The mechanical layout of the continuous gravimetric blender used in the present work is shown in Fig. 1, where an example of two component blending (the blue and the red one) is considered (see also Fig. 3). The device is made of two parts:

- a set of **primary meters** (from one to six), devoted to supply the correct flow of each component, which must be delivered in fixed proportion according to the given recipe;
- a secondary hopper (the **mixer**), where the various ingredient flows are mixed in a homogeneous blend with perfect additive dispersion. The mixed material is then fed to the extruder; it must be noticed that the extruder can draw different flow values of the mixed components, according to the extrusion throughput requested by its own control system.

Each primary meter is made of three parts: a **hopper**, containing the component; a **screw**, that delivers the materials proportionally to its revolution speed; a **DC motor** actuating the screw through a 10x gear. So, changing the motor speed, it is possible to change the screw speed and finally the material flow. The primary meter operation is based on the loss-in-weight measurement principle: the weight of the component hopper is measured in real-time; so, at least in principle, it is possible to compute the flow by weight measurement differentiation. Finally, since all the ingredient weights are continuously and simultaneously measured, it is expected that the total mass poured into the mixer is composed by the different ingredients in the correct ratios fixed by the recipe.

The mixer is endowed with a load cell that measures the mixer weight in order to prevent from undesired emptying; in fact, if the mixer does not contain enough material the blender could not be able to satisfy large flow variation requests from the extruder.

Finally, the blender is endowed with automatic pneumatic loaders to refill the primary meter hoppers when necessary.

A block diagram representation is shown in Fig. 2 for a two components blender. The control variables are the reference speed $\bar{\omega}_1(t)$ and $\bar{\omega}_2(t)$ of the DC motors, which are endowed with a speed control loop. The measurements $\omega_{m1}(t)$ and $\omega_{m2}(t)$ respectively of the revolution speeds $\omega_1(t)$ and $\omega_2(t)$ are affected by quantization noises $d_{\omega_1}(t)$ and $d_{\omega_2}(t)$. The metering screws deliver mass flow respectively $q_1(t)$ and $q_2(t)$, depending on their speed. The measurements $m_{m1}(t)$ and $m_{m2}(t)$ of the delivered masses $m_1(t)$ and $m_2(t)$ are affected by noises $d_{m_1}(t)$ and $d_{m_2}(t)$ due to the reduced resolution of the load cell and the mechanical vibrations of the structure (as detailed further in the paper).

The total mass flow $q_t(t)$ delivered to the mixer is the sum of the two partial metered mass flow $q_1(t)$ and $q_2(t)$. The extruder draw from the mixer the mass flow $q_e(t)$, while the load cell weights the mixer total mass $M(t)$, which measurement can be considered virtually noise-free for the aims of this work.

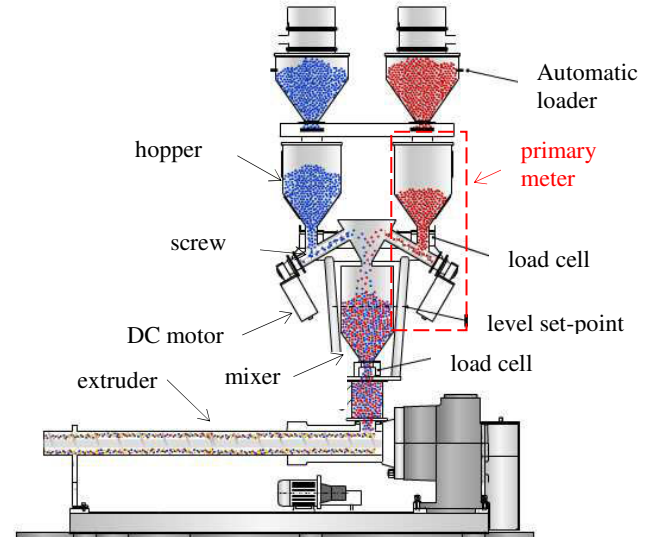


Figure 1. Schematic of the continuous gravimetric blender..

This plant has three main control objectives:

- first, each primary meter must deliver the ingredient to the mixer with the highest accuracy as possible;
- secondly, all the primary meters must deliver the ingredients according to the ratios defined by the recipe, in particular during flow changes following extruder requests;
- third, the mass variation of the blended components in the mixer, as a consequence of changes in the extruder flow, must be reduced as much as possible. In particular, the worst case, i.e. the larger possible change in the extruder flow, is a 2/3 reduction starting from the maximum flow.

The development of the control algorithm has not been performed connecting the blender to an extruder, because this would have determined a large plastic waste. So, in order to simulate the flow changes requested from an extruder, the mixer drain has been connected to a screw that draw away the blended components with variable flow depending on its revolution speed.

In the present paper, a two component continuous gravimetric blender is considered. The first component, the “bulk” one, is delivered by a primary meter with 300 kg/h of maximum flow; the second component, the “additive”, is delivered by a primary meter with 30 kg/h of maximum flow. The recipe is 91% bulk and 9% additive.

Currently, the plant is controlled in open loop. The performance of this control system will be discussed further in the paper.

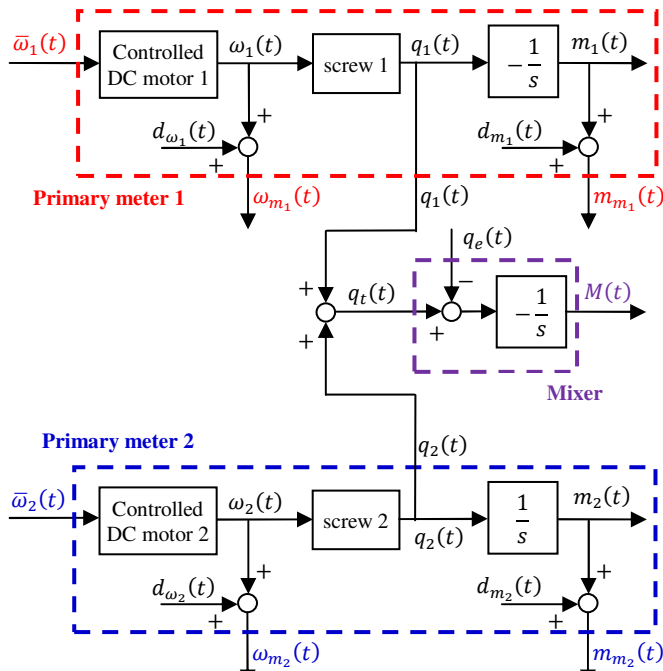


Figure 2. System theory representation of the considered plant.

3. PRIMARY METER CONTROL

The primary meter operation is based on a very simple principle: at a given screw revolution speed the meter delivers a constant volumetric flow, with a proportionality coefficient slightly changing with the screw speed, i.e.

$$\frac{dV(t)}{dt} = K_s(\omega(t))\omega(t) \quad (1)$$

where $\omega(t)$ is the screw revolution speed and $V(t)$ is the delivered component volume.

Since the aim is the control of the mass flow, Eq. (1) must be modified as follows

$$\rho \frac{dV(t)}{dt} = \rho K_s(\omega(t))\omega(t) \quad (2)$$

where ρ is the component density. So, from Eq. (2) it follows

$$q(t) = \frac{dm(t)}{dt} = K(\omega(t))\omega(t) \quad (3)$$

where $q(t)$ is the mass flow to be controlled and $K = \rho K_s$ is the proportionality constant that depend on the screw (which is fixed during normal operation), on the revolution speed and the material density, which are varying during normal operation. In particular, the screw revolution speed ranges from 0 to 300 rpm and the material density can vary from 500 g/l to 1500 g/l.

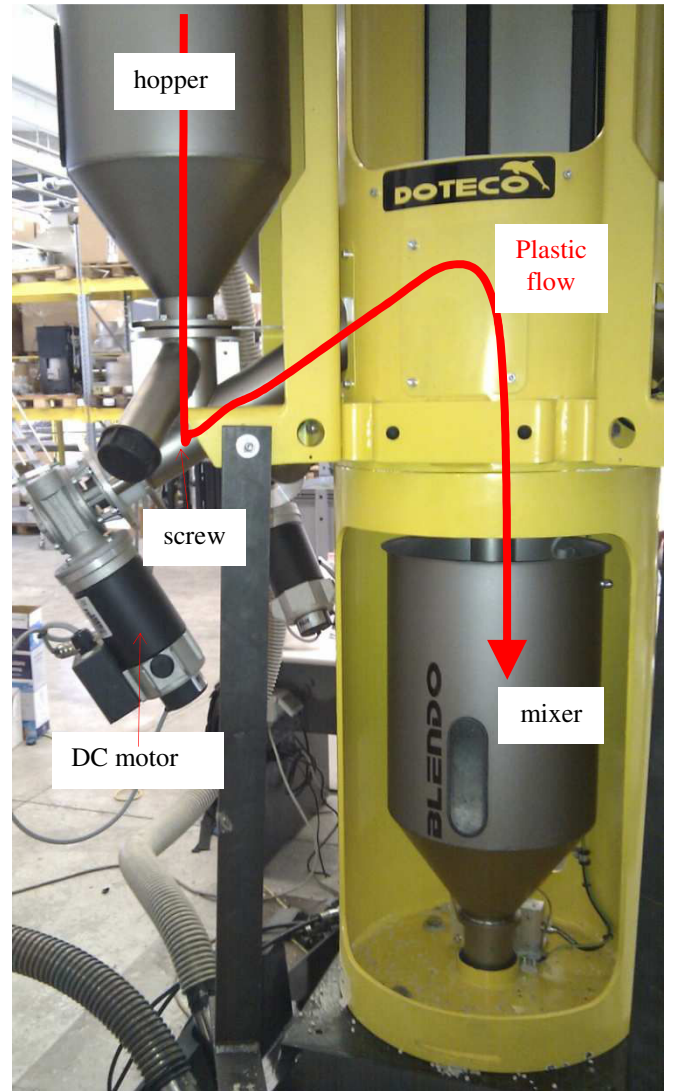


Figure 3. The continuous gravimetric blender used for testing the control algorithm developed in the present paper.

So, the control problem is made by two sub-problems:

- first, the mass flow $q(t)$ must be estimated;
- secondly, the estimated mass flow can be used to solve a closed loop regulation problem.

The mass flow could be estimated, in principle, by using the load cell measurement. In fact, the load cell measures the total weight of the primary meter (the component, the hopper and the motor-gear-screw system). So, by numerical derivation of the measured weight, the mass decrease could be estimated. Unfortunately, this is not feasible because of the peculiar mechanical layout of the system. In fact, the load cell, which supports all the weight of the meter, is fixed on one side to the plant structure and on the other side to the meter to weight. In this configuration, the vibrations produced by the screw rotation considerably disturb the load cell measurements.

Extend Kalman Filter could be designed [1,2], simultaneously estimating both $q(t)$ and $K(t)$, but this will be difficult to implement on the PLC used on the plant, which has strong computation limits [13].

So, we resort to a mixed strategy to estimate the flow mass (see Fig. 4): a standard KF has been designed to estimate the mass flow $\hat{q}(t)$ using a slowly varying estimate $\hat{R}(t)$ of the screw gain obtained by means of band-limited numerical differentiation. The equations describing the mass flow estimator are the following:

$$\frac{d\hat{m}(t)}{dt} = -\hat{q}(t) - K_2 e(t) \quad (4.a)$$

$$\frac{d\hat{q}(t)}{dt} = -\frac{1}{\tau} \hat{q}(t) + \frac{\hat{R}(t)}{\tau} \omega(t) + \frac{K_1}{\tau} e(t) \quad (4.b)$$

$$e(t) = m(t) - \hat{m}(t) \quad (4.c)$$

$$\hat{R}(t) = \frac{m_f(t)}{\omega_f(t)} \quad (4.d)$$

where the filtered mass $m_f(t)$ and the filtered speed $\omega_f(t)$ are obtained through the following filters:

$$\Omega_f(s) = \frac{1}{(1 + s\tau_f)^2} \Omega(s) \quad (4.e)$$

$$M_f(s) = \frac{s}{(1 + s\tau_f)^2} M(s) \quad (4.f)$$

where: $\tau_f = 5.4 \text{ s}$, $\tau = 0.1 \text{ s}$, $K_1 = 1$, $K_2 = 0.5$

Once that an estimate $\hat{q}(t)$ of the mass flow is available a closed loop controller can be designed according to the schematic representation of Fig. 5, where the controller is a PI controller [8,18] that decides the reference speed of the DC-motor control system.

The performances of the mass flow control are shown in Fig. 6 where a step response is presented in order to quantitatively show the settling time and the steady state error. In order to evaluate the accuracy of the mass flow regulator, at least at steady state, the component delivered by a meter in a measured time interval at constant reference flow has been collected and weighted. An example of these kind of tests is shown in Fig. 7: in the upper figure the weight measurement (blue solid line) is compared with the numerical integration of the estimated mass flow (red dotted line); in the lower figure the estimated mass flow is depicted. The measured mean mass flow is 233.2 g/h; the estimated mean mass flow is 232.4 g/h.

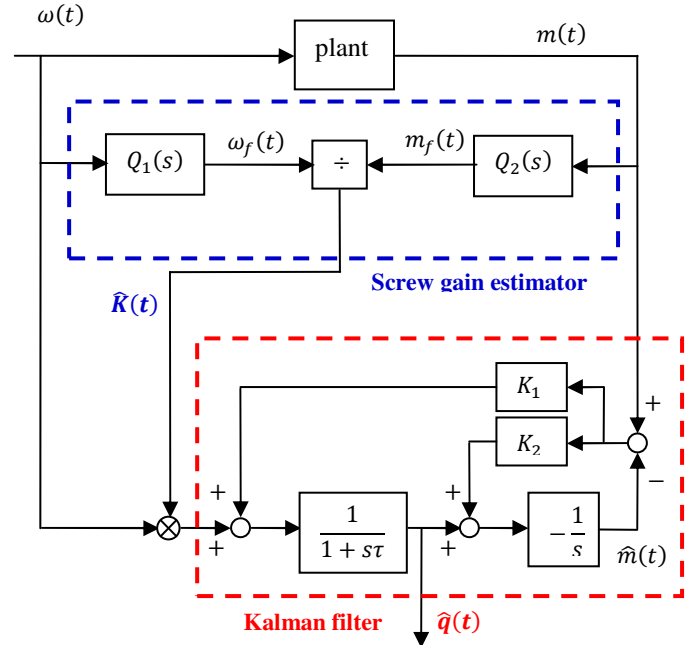


Figure 4. Schematic representation of the mass flow estimator.

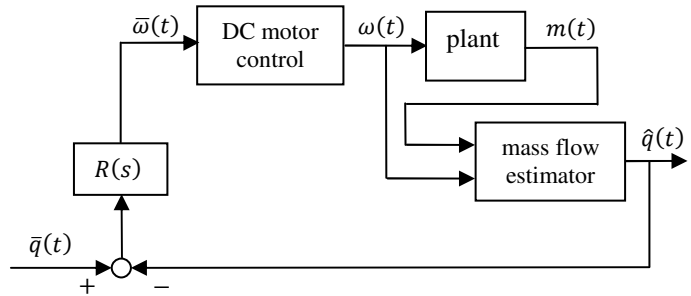


Figure 5. Schematic representation of the mass flow closed loop control system.

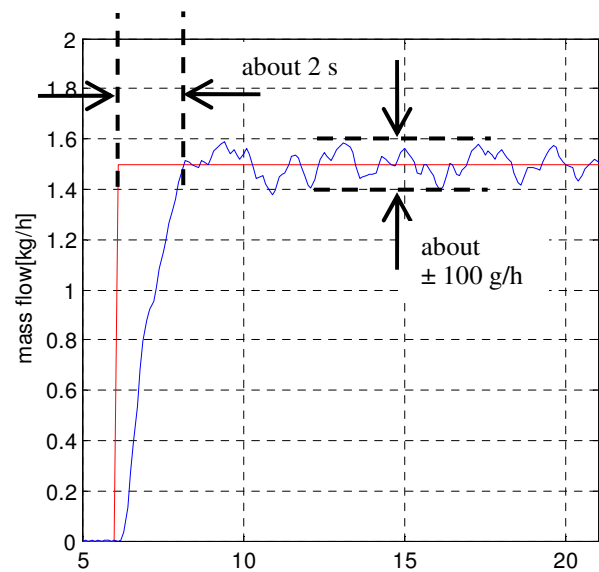


Figure 6. Step response for the additive primary meter.

In order to guarantee that the ratios of the components delivered by the meters are in agreement with the requirements of the assigned recipe, the reference signal of the mass flow control loop have been pre-filtered. So, the flow request to the control loop is $\bar{q}_f(t)$ with

$$\bar{Q}_f(s) = \frac{1}{1 + s\tau_s} Q_f(s) \quad (5)$$

The time constant of this servo system must be chosen carefully. In particular, it has been chosen considering the worst ever case for the control system, i.e. the lowest density material with the smallest screw. In this case, the transient time of the closed loop system will be the larger (about 15 s) and consequently the time constant has been set to $\tau_s = 3.5$ s. In Fig. 8 are shown the estimated mass flow transient responses of both the primary meters. The signal of the additive meter (0-30 kg) has been multiplied by the recipe ratio (91/9) in order to plot it together with the estimated flow response of the bulk meter (0-300 kg). As evident there is a perfect superposition of the two signals even during the transient.

4. MIXER HOPPER CONTROL

The mixer receives the plastic granulate from the primary meters and delivers the plastic blend to the extruder. The extruder requests to the blender a variable plastic mass flow depending on its operating conditions which are determined by its own control system. The aim of the mixer controller is to avoid extreme emptying of this hopper, so that it is always ready to satisfy the plastic flow request from the extruder. In particular, the worst case that must be considered is the reduction of the flow requested by the extruder from 100% to 30%. This variation is a typical operation condition in three line extruders, when two lines are suddenly switched off. Since the mixer weight is measured by a load cell, this goal can be fulfilled by designing a mass controller.

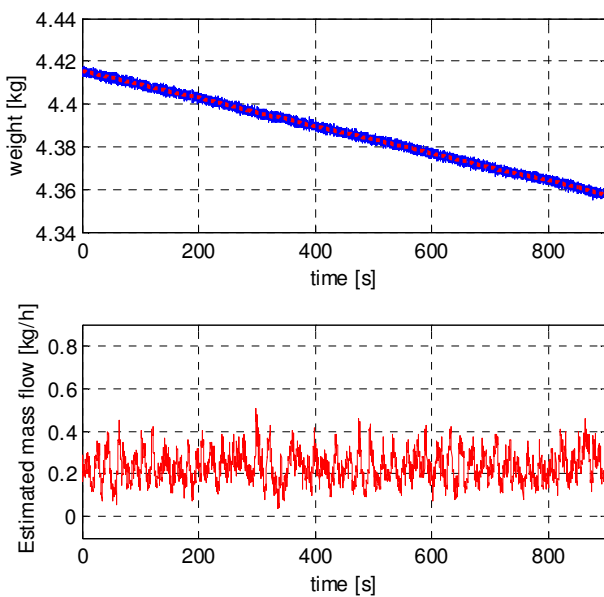


Figure 7. (Bottom) Estimated mass flow. (Top) Load cell measurement (solid-blue) and numerical integration of the estimate (red-dotted).

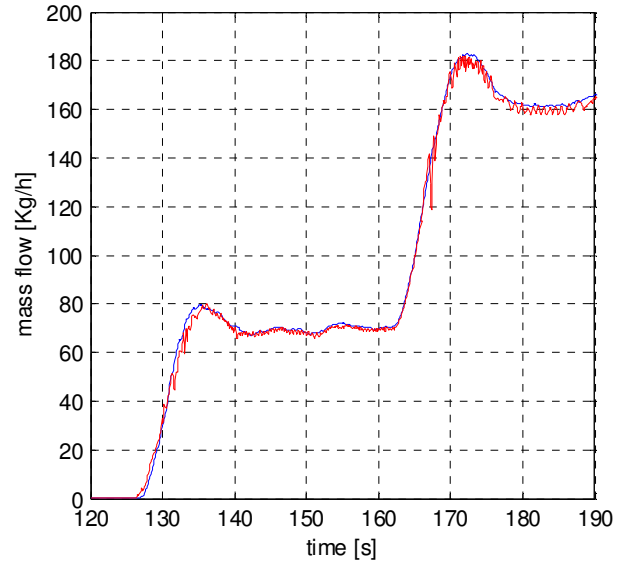


Figure 8. Comparison between the bulk meter flow (blue) and the additive meter flow (red) multiplied by the recipe ratio (91/9).

A secondary objective is also to reduce the mixer dimensions, i.e. to limit the errors between the reference weight and the measured one.

The equation governing the mixer dynamics is very simple:

$$\frac{dM(t)}{dt} = q_t(t) - q_e(t) \quad (6)$$

where $M(t)$ is the mixer weight; $q_t(t)$ is the total flow coming from the primary meters; $q_e(t)$ is the flow going to the extruder, i.e. it acts as a disturbance on the system. The system described by Eq. (6) can be controlled by a P controller, as depicted in Fig. 9. The choice of a P controller is obliged, since there is an integrator in the loop [18]. Moreover, the control system will have finite and different from zero steady state error since the extruder flow disturbance is integrated in the loop.

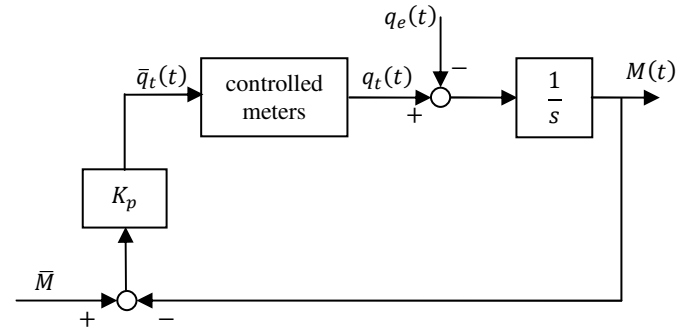


Figure 9. Schematic representation of the mixer weight control loop.

In Fig. 10, the performances of the mixer controller are shown. In this test, the extruder screw has been set to its maximum revolution speed (100%) with a mass reference value $\bar{M} = 3$ kg and with $K_p = 1000$. Then, at about $t=100$ s the screw speed has been reduced to the 25% of its maximum

speed. Finally, the speed has been raised again to 75% of its maximum.

In Fig. 10 the mixer weight is shown. Notice that, as expected, the steady state error is about 10% of the set point value, i.e. 0.3 kg. Obviously, the steady state error is always positive. The transient time is about 20 s.

5. CONCLUDING REMARKS

In this paper, the control system for a continuous gravimetric blender has been designed from scratch. In particular, a cascade control system has been realized. This is made by an inner loop, devoted to the regulation of the mass flow delivered by all the meters in the plant and by an outer loop which keep constant the weight in the hopper which delivers the plastic granulate to the extruder, rejecting the flow disturbances caused by the extruder itself. Moreover, for the operation of the inner control loop mass flow has been estimated by resorting to a mixed approach involving both Kalman Filtering and numerical differentiation.

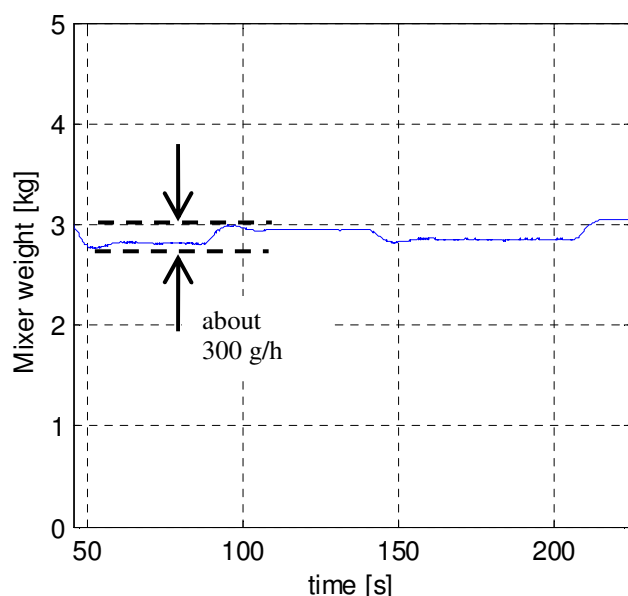


Figure 10. Mixer weight measurement as a response to extruder flow disturbances.

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