

## Gain Scheduling Control of a Gravimetric Blender with Vibrant Duct

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Abstract: Blender and feeder are very important devices in a polymer processing plant. The accuracy in delivering the polymer to the plastification unit is a fundamental property for the quality of the final product. To maximize accuracy and precision gravimetric feeder are the best available solution, which measure the weight of the hopper and the feeder. In these devices, it is possible to estimate the delivered flow based on a loss-in-weight method and to design closed loop control systems to regulate the polymer flow. Specifically, in this work vibrating duct feeder are considered which show a peculiar nonlinear dynamics due to the vibrating element. Then, a nonlinear gain scheduling controller has been designed using an implementation which guarantee satisfaction of the so called linearization property.

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### 1. INTRODUCTION

In many polymer transformation processes, i.e. injection moulding, blow moulding and film processing, extruders (or more generically plastification units) are necessary to melt the material and push it towards the output die, by means of a rotating screw, where the extruded final product is shaped and forwarded to the final processing step. During the plastification process, the polymer undergoes very complex thermo-mechanical transformations inducing strong changes in the physical properties of the material, which have great influence on the final product quality ([4] and [9]). 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. Blenders are key elements in the plastic extrusion process since they decide both the proportion of the different components in the final blend and the quantity of material per unit time that must be processed ([3], [5]).

The final product quality in polymer processing is strongly dependent on the precision of metering and blending of the polymer through the extruder ([6], [8] and [9]). So, accurate regulation of the mass flow delivered from the blender to the extruder is strongly advised. Usually, from two to six different polymeric components are blended in the feeding section by means of gravimetric or volumetric systems. 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 poor in many operating conditions, in particular during changes in the flow requested by the extruder.

In this work, gravimetric blenders with vibrant ducts are considered: the hopper weight is measured and the plastic flow is usually computed according to a loss-in-weight rationale and finally the polymer is transported along a duct by means of a vibrator and delivered to the extruder. The gravimetric blenders can provide accurate flow control by means of closed loop control: so, 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. 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. Finally, the material savings preserve the environment from pollution due to unnecessary plastic waste.

In order to perform closed loop flow control, it must be noticed that vibrating duct of gravimetric meters shows a nonlinear dependence of the mass flow on the amplitude of the vibration. In particular, respectively at low and high vibration amplitudes, the flow sensitivity to amplitude is very small and so the controller gain must be increased.

In this paper, the control system design problem for a gravimetric blender with vibrant duct is considered by resorting to a gain scheduling method. First of all, a nonlinear model of the plant is designed. Then, based on the model, a nonlinear feedback controller is designed to work on a wide operating range of the system directly using weight measurements. In particular, first, a set of linear pole placement regulators is designed for the models obtained by linearizing the model about different operating points. Then, starting from such linear regulators a gain scheduling

controller is defined following the approach described in [12]. Such a gain scheduling design is performed so that the linearization property is verified, i.e., at each equilibrium point, the nonlinear gain scheduling feedback system exhibits the same internal and I-O dynamic properties of the corresponding locally designed linear control loop. The overall performance of the proposed controller has been experimentally validated.

Notice that the proposed control design method is applicable to all gravimetric blenders, i.e. also to screw or belt feeders.

In short, this paper is organized as follows. Section 2 summarizes the basic experimental setup. In Section 3, the plant model is designed. Section 4 and 5 are devoted to the proposed gain scheduling control scheme and its application to the vibrating duct feeder. Finally, Section 6 shows experimental validation and some concluding remarks are drawn in Section 7.

## 2. EXPERIMENTAL SETUP

The mechanical layout of the continuous gravimetric feeder used in the present work is shown in Fig. 1, where an example of a two component blender (the blue and the red one) is considered. The device consists of different meters (from two up to six) whose operation is based on the transport of the material by vibrant ducts. Each meter is made of three parts: a **hopper**, containing the material; a **vibrator**, composed of a DC motor that moves a variable eccentric mass and a **duct** connected to the vibrator necessary to material transport. The material flows coming from the different blenders are finally collected in a mixer and then delivered to the extruder.

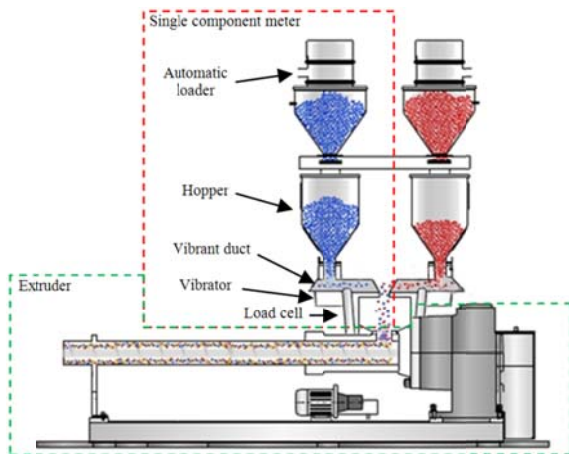


Fig. 1. Mechanical layout

The machine operation is based on the following steps: the control of the extrusion line establishes the total material flow of the blender; the total flow required is split to all feeders on the basis of the established recipe; each meter must ensure the delivery of the required flow-rate.

In these particular blenders (gravimetric feeders) the material is moved by the weight force generated by the material contained in the hopper: the vibrator is needed just to regulate the material flow since it does not contribute actively to the

movement. In order to control the material flow of the single component meters, the gravimetric feeder has been equipped with a capacitive load cell to measure the instantaneous weight of the hopper and a piezoelectric accelerometer to acquire the amplitude of the vibration generated by the vibrator. Moreover, a Kalman Filter estimator has been developed to estimate the material flow exiting from the duct [10]. A control strategy for gravimetric feeders has been already proposed in [11], where a PID regulator generates the command signal of the vibrator to obtain the desired material flow. However, this strategy presents some performance limits due to the non-linear dynamic of the actuator: in particular, considering different operating points, the closed loop system bandwidth and step response time are largely different. This behavior is not acceptable in a gravimeter feeder system, where all the material components have to be precisely dosed maintaining the correct proportion with respect to the recipe and to obtain the desired plastic material properties in the extrusion process. For this reason, a more accurate control strategy is required to get the same dynamical performance in each operating condition and in this work a gain scheduling control method based on pole placement design is used as described in Section 4.

For this control strategy, the mass signal provided by the hopper load cell is used as feedback for the closed loop system because it is the only available measurement of the material weight and flow. However, the control target for a gravimetric feeder is to regulate the material flow: for this reason, the control system performance will be evaluated in terms of material flow. The other available system information (actuator vibration from the accelerometer and material flow from the Kalman Filter estimator) are also utilized from the regulation to assign the desired dynamic of the closed-loop system.

## 3. MATHEMATICAL MODEL

In order to describe the dynamical behavior of the plant and to design the proper control strategy, a mathematical model of the gravimetric blender has been developed. A physical approach has been adopted, considering the features of the main components (hopper, vibrator and duct), as represented in Fig. 2.

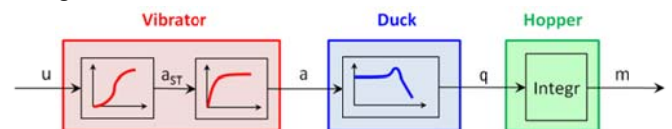


Fig. 2. Scheme of the mathematical model

The vibrator is activated by the electrical input signal  $u(t)$  and generates an acceleration of fixed frequency (100Hz) and variable amplitude  $a(t)$ . From experimental data obtained with the acquisition of the accelerometer signal at different input command values, it is possible to note a non-linear behavior of the vibrator. In particular, for low input value (from 0% to 30%) the acceleration is close to zero and practically negligible; for medium input range value (from 35% to 75%), the vibration amplitude increases abruptly; for high input value (greater than 80%), the acceleration keeps

close to the maximum value. The experimental characteristic between actuator command  $u(t)$  and the static value of the vibration  $a_{ST}(t)$  has been interpolated with an hyperbolic tangent function and in according with (1): the result is shown in the graphical comparison of Fig. 3.

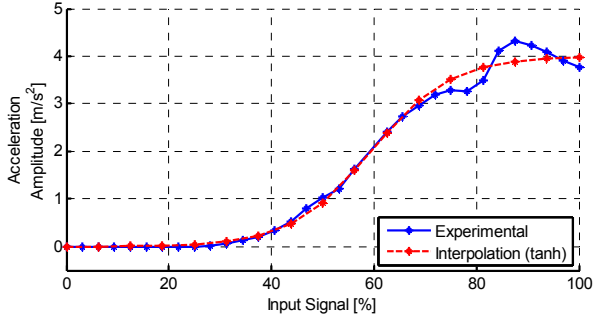


Fig. 3. Static characteristic of the actuator

$$\begin{cases} a_{ST}(t) = k_V(u(t)) \\ k_V(u) = a_0 + a_1 \cdot \tanh(b_0 + b_1 \cdot u) \end{cases} \quad (1)$$

Moreover the actuation system presents a transient due to electro-mechanical dynamic. Then, the overall dynamical behavior of the vibrator can be modeled with two components: a non-linear gain, which represents the static characteristic  $k_V(u)$ , and a dynamic term, according to:

$$\dot{a}(t) = -\frac{1}{\tau_V} \cdot a(t) + \frac{1}{\tau_V} \cdot a_{ST}(t) \quad (2)$$

where  $a(t)$  and  $a_{ST}(t)$  are the measured acceleration and the static acceleration value respectively and  $\tau_V$  is the time constant of vibrator actuation system.

The vibrator is rigidly connected to the duct, which provides to the mixer a material flow  $q(t)$  proportional to the vibration amplitude  $a(t)$ . Nevertheless from the dynamical tests, a peak resonance has been discovered: then the duct dynamic has been model as in (3).

$$\ddot{q}(t) = -2\xi\omega_n \cdot \dot{q}(t) - \omega_n^2 \cdot q(t) + k_D\omega_n^2 \cdot a(t) \quad (3)$$

where  $k_D$ ,  $\omega_n$  and  $\xi$  are the gain, resonance frequency and damper of the duct respectively.

The material flow  $q(t)$  exiting from the duct is extracted from the hopper: considering the mass balance, the hopper mass  $m(t)$  can be obtained by integration, as described in (4).

$$\dot{m}(t) = -q(t) \quad (4)$$

The complete non-linear model is summarized in (5). The model parameters  $\tau_V$ ,  $k_D$ ,  $\omega_n$  and  $\xi$  of the mathematical model have been identified by minimizing the error between model simulation and experimental response to different steps variation.

$$\begin{cases} a_{ST}(t) = k_V(u(t)) \\ \dot{a}(t) = 1/\tau_V \cdot (a_{ST}(t) - a(t)) \\ \ddot{q}(t) = \omega_n^2 \cdot (k_D \cdot a(t) - q(t)) - 2\xi\omega_n \cdot \dot{q}(t) \\ \dot{m}(t) = -q(t) \end{cases} \quad (5)$$

Finally, the mathematical model has been validated considering a different input signal (sinusoid), as shown in Fig. 4.

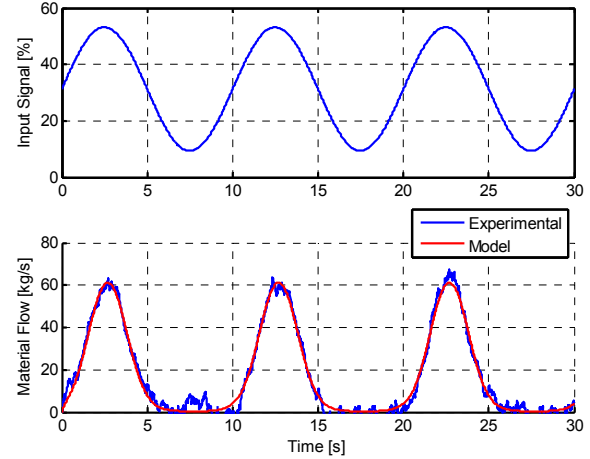


Fig. 4. Mathematical model validation

#### 4. GAIN SCHEDULING CONTROL SYSTEM DESIGN

The gain scheduling approach is one of the most popular techniques in nonlinear control, and it has been successfully applied in several applications where the dynamic behavior of the plant changes with the operating regime ([13] and [15]). Basically, the design of a gain scheduling controller is done according to the following rationale: select a number of equilibrium points covering the operating range of the nonlinear plant and compute a set of linear tangent approximating models of the plant in these equilibrium points; design a set of linear controllers according to some design criterion and feedback property; interpolate the different local loops, i.e., change (schedule) the parameters (gains) of the local controllers. The interpolation relies upon an exogenous variable capturing the plant operating conditions, called scheduling variable ([12], [14] [16] and [17]).

In this work, a gain scheduling controller is designed by following the approach presented in [16] using the controller input as scheduling variable. Specifically, a set of linear tangent models are computed on the basis of the non linear model presented in Section 3; then local controllers are designed using pole placement. Finally, the nonlinear controller gains are obtained by properly interpolating the gains of the linear regulators as a function of the scheduling variable. The key issue of the method applied in this work, is the "velocity" implementation of the nonlinear controller. In fact, since the linear regulators operate on the perturbations of the plant input and output, differentiation is performed on the feedback variables, so that the linear controllers have access to small variations of the global variables. Integral action is provided at the plant input, resulting in zero steady-state error and preserving the I/O transfer functions at the operating points.

In order to design the nonlinear controller, first of all consider the nonlinear system

$$G := \begin{cases} \dot{x} = f(x, u) \\ y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_1(x, u) \\ h_2(x, u) \end{bmatrix} \end{cases} \quad (6)$$

where  $y_2$  is the output we desire to control and  $y_1$  are other measurable outputs. Consider a set of equilibrium points parameterized by a scheduling variable  $\alpha(t)$  (7):

$$E = E(\alpha_0) := \{(x_0, u_0) : f(x_0, u_0) = 0, (x_0, u_0) = g(\alpha_0)\} \quad (7)$$

being  $\alpha_0$  the set of values of the scheduling variable in correspondence of the equilibrium points. Specifically, in this paper the controlled input will be used as a scheduling variable. So, a set of linear tangent models can be computed on the basis of (6)

$$G_{L\alpha_0} := \begin{cases} \dot{\xi} = A(\alpha_0) \cdot \xi + B(\alpha_0) \cdot \eta \\ \theta_1 = C_1(\alpha_0) \cdot \xi + D_1(\alpha_0) \cdot \eta \\ \theta_2 = C_2(\alpha_0) \cdot \xi + D_2(\alpha_0) \cdot \eta \end{cases} \quad (8)$$

being  $y_0 = \begin{bmatrix} y_{10} \\ y_{20} \end{bmatrix} = \begin{bmatrix} h_1(x_0, u_0) \\ h_2(x_0, u_0) \end{bmatrix}$  the equilibrium values for

the output;  $\eta = u - u_0$ ,  $\xi = x - x_0$ ,  $\theta_1 = y_1 - y_{10}$  and  $\theta_2 = y_2 - y_{20}$  are the small variation signals.

Then, the state equations of the linear systems family is enlarged in order to accommodate integral action

$$\begin{bmatrix} \dot{\xi} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} A(\alpha_0) & 0 \\ -C_2(\alpha_0) & 0 \end{bmatrix} \cdot \begin{bmatrix} \xi \\ v \end{bmatrix} + \begin{bmatrix} B(\alpha_0) \\ -D_2(\alpha_0) \end{bmatrix} \cdot \eta + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \cdot \rho \quad (9)$$

being  $\rho$  the small variation reference signal. For each enlarged linear tangent model, a linear controller is computed by means of pole-placement method. The linear controller structure is the following:

$$\eta(t) = K_x(\alpha_0)\xi(t) + K_v(\alpha_0)v(t) = K(\alpha_0)\xi_E(t) \quad (10)$$

The controller gains are designed according to the following criterion

$$K_x, K_v : eig \left( \begin{bmatrix} A & 0 \\ -C_2 & 0 \end{bmatrix} + \begin{bmatrix} B \\ -D_2 \end{bmatrix} \cdot [K_x \quad K_v] \right) = P \quad (11)$$

being  $P$  a set of suitable values for the system closed loop poles.

The gains of the linear controllers are interpolated as a function of the scheduling variable using a polynomial function as described in the following Section 5. So, a variable gain function  $K=K(\alpha)$  is obtained and the nonlinear controller is implemented as described in Fig. 5.

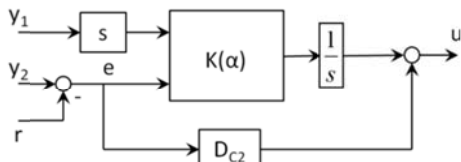


Fig. 5. Gain scheduling controller for the non-linear system

## 5. APPLICATION TO GRAVIMETRIC FEEDERS

### 5.1 Linearized System and Pole Placement Control

In this section, a local linear model is first obtained starting from the identified non-linear model by linearization about an

equilibrium point. Then, for such a local linear model, an eigenvalue assignment (pole placement) regulator is designed in order to obtain the desired dynamic of the closed loop system.

By linearizing the non-linear model about the equilibrium point  $\alpha_0$ , the linear tangent model with state-space representation of (8) is obtained, where the system matrix are defined as:

$$A = \begin{bmatrix} -1/\tau_V & 0 & 0 & 0 \\ k_D \omega_n^2 & -2\xi \omega_n^2 & -\omega_n^2 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad B = \begin{bmatrix} k_{V0}/\tau_V \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (12)$$

$$C_2 = [0 \quad 0 \quad 0 \quad 1] \quad C_1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad D_1 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$D_2 = 0$$

and the state variables are the small variation signals of  $x = [a \quad \dot{q} \quad q \quad m]^T$ . The linear tangent model is used to design the stabilizing controller to assign the desired dynamic defined by the pole position  $P$  to the closed-loop system.

In the reminder of this section, the design procedure for the pole placement regulator is outlined by means of an example. In particular, the considered equilibrium condition is defined by the input value  $u_0 = 60\%$ , the corresponding output material flow  $q_0 = 98.73\text{kg/h}$ , and the parameters of the corresponding linearized model are summarized in Table 1

Parameter	Unit	Value
$u_0$	%	60
$q_0$	kg/h	98.73
$k_{V0}$	$\text{m}^2/\text{s}^2 / \%$	0,12
$\tau_V$	s	0,0125
$k_D$	$\text{kg/h} / \text{m}^2/\text{s}^2$	48,804
$\omega_n$	rad/s	79,83
$\xi$	-	0,107

Table 1 – Parameters of the linear tangent model

The closed-loop system is required to present a settling time lower than 1s, then the poles position  $P$  has been fixed in order to obtain a dominant pole with time constant lower than 0.2s and other negligible poles at high frequency

$$P = [-8 \quad -50 \quad -55 \quad -60 \quad -65]$$

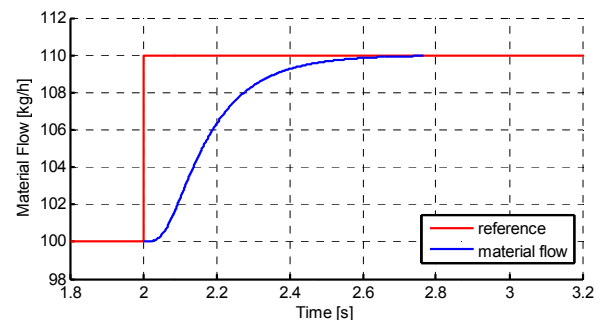


Fig. 6. Step response of the linear closed-loop system.

The corresponding value obtained for  $K_X$  and  $K_V$ , for the considered example are:

$$K_X = [125.6 \quad -0.519 \quad -2.708 \quad -5.610], \quad K_V = 28.736$$

The step response of the local closed-loop system made with the linear tangent model and the corresponding pole placement regulator is shown in Fig. 6.

### 5.2 Gain Scheduling on the Non Linear System

In order to design the gain scheduling controller, the non-linear system (6) has been taking into account, considering the mass  $m(t)$  as the controlled variable and the remaining state variables  $a(t), q(t), \dot{q}(t)$  as measured ones. For a set of 7 equilibrium points parameterized on the input variable  $\alpha_0 \equiv u_0 = [10 \quad 25 \quad 40 \quad 55 \quad 70 \quad 85 \quad 100]$ , the linear tangent models and the corresponding regulators gains have been calculated. The resulting parameters values are reported in Table 2.

Notice that, as expected from the shape of the nonlinear part of the system (see Fig. 3), the controller gains are larger for both small and large vibration amplitude. Then, the parameters of the regulators designed on the linear tangent models corresponding to the different equilibrium points have been interpolated, in order to obtain controller parameters in function of the variable  $\alpha$  (which correspond to input variable  $u$  in this particular situation) that defines the operating point.

Point	$u_0$	$q_0$	$K_X$			$K_V$	
1	10	0,48	12731	-52,63	-274,49	-568,64	2912,6
2	25	2,88	2153,3	-8,91	-46,51	-96,35	493,55
3	40	16,23	411,78	-1,71	-8,87	-18,393	94,21
4	55	69,17	137,25	-0,56	-2,96	-6,13	31,42
5	70	150,02	176,51	-0,73	-3,8	-7,88	40,38
6	85	185,95	695,06	-2,87	-14,96	-31,04	159,02
7	100	193,62	2878,6	-16,03	-83,62	-173,24	887,36

Table 2 – Operating points and controllers parameters

The interpolating function  $K(\alpha)$  should be continuous and differentiable in order to preserve the linearization properties ([12] and [17]): for this reason, a 4th order polynomial function has been adopted. Notice that each component of the of the gain vector  $K$  has its own interpolating polynomial, obtained from the values at the different operating points. An example of the interpolating function regarding the controller parameter  $K_V$  is shown in Fig. 7.

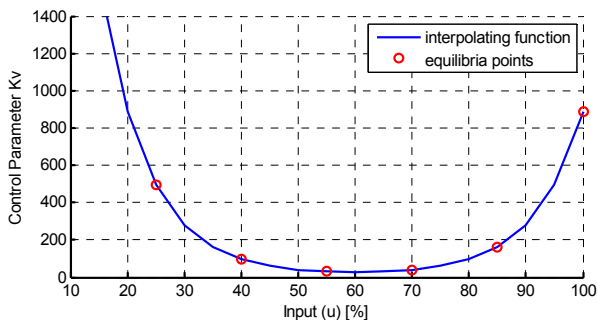


Fig. 7. Interpolating function for the gain-scheduling controller parameter  $K_V$

Finally, the controller parameters which vary in function on the operating condition has been inserted in the control scheme shown in Fig. 5, obtaining the gain-scheduling regulator for the non-linear system.

## 6. CONTROLLER PERFORMANCE EVALUATION

The gain-scheduling controller has been designed to obtain the desired closed-loop system dynamic imposed with the pole placement methodology in each operating conditions. The most different and critical operating conditions are the low (and high) range of input (from 0% to 30% and from 80% to 100%), where the plant has a reduced sensitivity to the input variations, and the medium range of input (from 40% to 75%), where the plant presents and elevated gain.

For this reason, the gain-scheduling controller has been tested on the real plant in both the conditions, applying different steps to the required material flow reference. The experimental results show that the closed-loop system correctly tracks the reference signal and maintains the desired dynamic behavior (settling time) in each operating condition, due to the significant variation of the control parameters, as shown in Fig. 8.

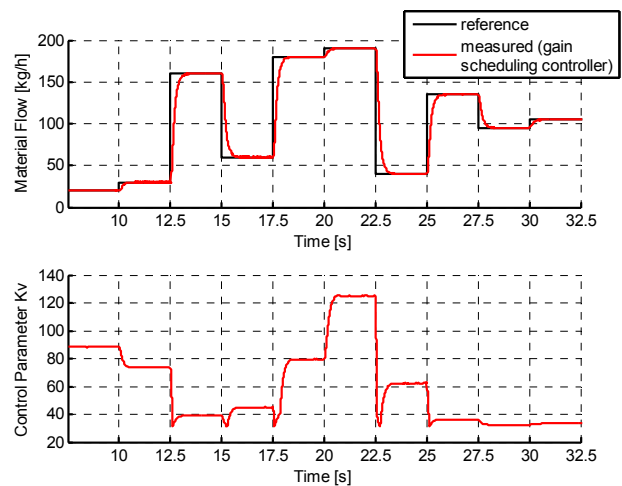


Fig. 8. Step response of the gain-scheduling controlled system and parameter variation

Moreover, the gain-scheduling controller has been compared to two different linear pole-placement controllers designed on the local linear tangent systems, as described in section 5.1. In particular, with the three different regulators, that are the gain-scheduling controller (red line), the linear pole placement controller designed for low material flow (blue line) and linear pole placement controller designed for medium material flow (green line): the results are illustrated in Fig. 9.

The linear controllers properly work in the operating conditions where they have been design but presents overshooting or oscillation in the other condition. On the contrary, the gain-scheduling controller ensures good dynamic behavior in both the operating conditions without oscillation or overshooting.

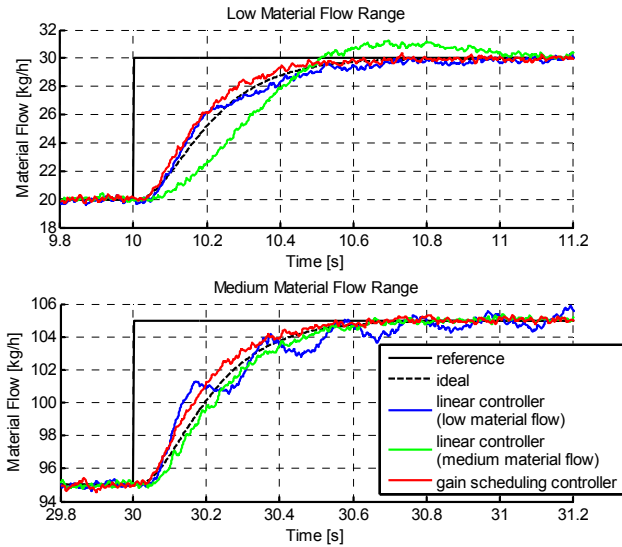


Fig. 9. Comparison of the step response of the different controlled system in different operating condition.

Since each controller has been designed to obtain the same closed-loop dynamic (defined by the pole position  $P$ ), a model reference considering ideal behavior has been implemented and the corresponding step response (black dashed line) has used to quantify the controllers performance considering the mean squared error between model reference  $y_{MM}$  and controlled closed-loop system  $y_{CCLS}$ , defined as:

$$MSE = \frac{\sum_{k=1}^N ((y_{CCLS}(k) - y_{MM}(k))^2)}{N} \quad (13)$$

The performance evaluation, shown in Table 3, evidences the effectiveness of the gain-scheduling controller in each operating condition whereas the local linear controllers presents a small error just in the operating condition where they have been designed.

MSE [kg <sup>2</sup> /h <sup>2</sup> ]	Low Range Step 20 kg/h => 30 kg/h	Medium Range Step 95 kg/h => 105 kg/h	Overall Test
Linear Controller for Low Range	0,0121	0,5148	0,4009
Linear Controller for Medium Range	1,2835	0,0128	0,3537
Gain Scheduling Controller	0,0191	0,0198	0,0206

Table 3 – Controllers performance evaluation

### 7. CONCLUSIONS

In this work, a gain scheduling control method based on the pole placement has been applied to a gravimetric feeder with vibrant duct, guaranteeing the respect of the linearization property of the nonlinear controlled system.

Experimental validation has been performed and has evidenced that the designed controller guarantee the desired performance in all the operating conditions, in particular at small flow values is able to give similar performances at large flows. Notice that differentiation of the measured variables does not affect the control system performances.

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