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Auto-tuning control systems for improved operation of continuous fluidized bed spray granulation processes with external product classification

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Abstract

In this contribution control of continuous fluidized bed spray granulation processes with external product classification is studied. From a practical point of view control schemes being easy to implement and maintain using standard process control systems are preferable. Hence, the focus will be on standard PI control structures. In order to account for variations and uncertainties in the process an additional tuning procedure should be included. Here, an optimization based online controller adaptation scheme called iterative feedback tuning (ITF) will be investigated.

Keywords: fluidized bed spray granulation; control; auto-tuning;

1. Introduction

Fluidized bed spray granulation is an important process for food production and in chemical and pharmaceutical industries. Here, a gas flow is used to fluidize a solid bed of initial particles. The resulting fluidized bed has the

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advantage of an enlarged active surface caused by increased bed porosity and good particle mixing. Injecting a liquid matter onto the fluidized particles allows a granulation processes, i.e. a particle size enlargement.

In order to produce particles with a well-defined particle size distribution granules being too big have to be milled. This can be achieved by sieving all particles being withdrawn from the process resulting in three fractions

1. Fines fraction, i.e. particles being smaller than the desired product,
2. Product fraction, i.e. particles of desired size,
3. Oversize fraction, i.e. particles being bigger than the desired product.

After the sieving product particles are removed, fine particles are directly fed back to the granulation chamber and oversized granules are send to a mill. After being grinded to a specific size the oversize fraction is send back to the granulation chamber. For a continuous process operation it is of great importance that the described sieve-mill cycle guarantees a permanent generation of new particles. In order to keep the overall bed mass constant a mass controller is often implemented using the rate of removed particles as the control variable.

It is well known [1,2] that for this particular configuration operational regimes are sensitive to unforeseen disturbances and variations in process parameters. Thus, for example, time transients in the particle size distribution may vary or instabilities resulting in nonlinear oscillations in the particle size distribution may occur. Therefore, use of appropriate control systems is highly desirable. In [3-7] several linear and nonlinear, early and late lumping control approaches have been presented for different particulate processes. As has been shown in [3,7] the continuous fluidized bed spray granulation may be controlled apply standard PI control. However, as will be shown in this contribution a model-based controller design method may greatly benefit from an additional controller tuning at the real plant in the presence of model uncertainties or process variations.

This paper is structured as follows: in section 2 the process and its population balance model is stated with typical modelling assumptions. In section 3 an optimization based controller auto-tuning method called the iterative feedback tuning method is described. Applying this iterative feedback tuning method to the continuous fluidized bed spray granulation it will be shown how an initially poorly tuned controller can be adapted to a given process situation.

Nomenclature

L	particle coordinate
t	time
n	particle size distribution
μ_i	i-th moment of the particle size distribution
G	growth rate
$\dot{n}_*$	particle fluxes
T_*	sieving function
n_M	particle size distribution of milled particles
$K(s)$	controller transfer function
$G(s)$	process transfer function
J	value function
e	control error
u	control input

2. Fluidized bed spray granulation

In the granulation chamber the initial particles are fluidized through an air stream with predefined pressure, temperature and humidity. Then a liquid solution is injected, which settles on the particles. Due to the low humidity and high temperature of the fluidization gas the liquid fraction evaporates resulting in a formation of a new solid layer on the particle surface (Fig. 1).

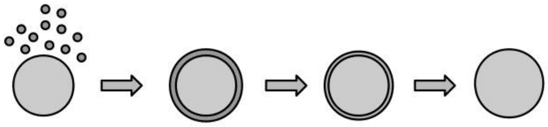

Figure 1. Layered growth mechanism

In parallel to this layered growth mechanism other micro processes like nucleation due to spray drying, particle agglomeration or breakage may take place. In order to derived a specific product particle size distribution particles withdrawn from the granulation chamber have to be sieved, which results in two additional fractions. The fine particles are directly sent back to the granulation chamber; whereas the oversized granules are send to a mill. There they are grinded to a specific size before being sent back to the granulation chamber. Due to this sieve-mill cycle a permanent generation of new particles is guaranteed, which hence allows a continuous process operation. The associated pilot plant and process scheme is depicted in Fig. 2 (left and right).

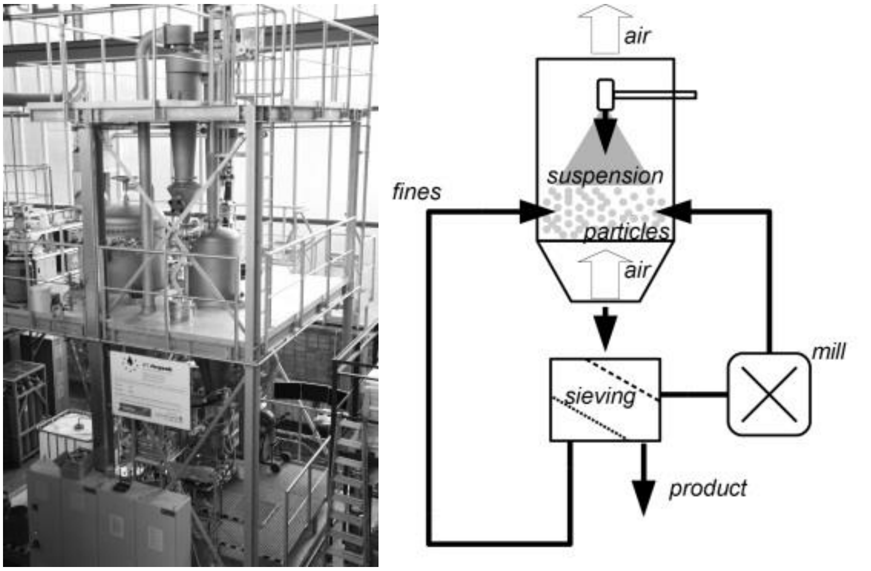

Figure 2. Pilot plant operated by NaWiTec at the University of Magdeburg (left) and process scheme of fluidized bed spray granulation with external product classification (right)

For the fluidized bed spray granulation with external product classification a population balance model has been presented in [1]. There, it was assumed that the particles are almost spherical and can hence be described by one internal coordinate L, the particle diameter, giving rise to the particle size distribution $n(t, L)$. The associated particle growth can be described by

$$G = 2\frac{\dot{m}_e}{\rho\pi\mu_2} \quad (1)$$

where μ_2 is the second moment of the particle size distribution $n(t, L)$ and $\dot{m}_e$ is the effective solid matter injection rate. The particle flux being removed from the granulator is

$$\dot{n}_{out}(t, L) = K\, n(t, L) \quad (2)$$

where K is the drain, which has to be chosen such that the bed mass is constant. The removed particles $\dot{n}_{out}(t, L)$ are then sieved in two sieves and separated into three classes: fines fraction eq. (3), i.e. particles which are smaller than the desired product, product fraction eq. (4), i.e. particles with the desired size and oversize fraction eq. (5), i.e. particles being bigger than the desired product.

$$\dot{n}_{fines}(t, L) = (1 - T_2(L))(1 - T_1(L))\, \dot{n}_{out}(t, L) \quad (3)$$

$$\dot{n}_{prod}(t, L) = T_2(L)(1 - T_1(L))\, \dot{n}_{out}(t, L) \quad (4)$$

$$\dot{n}_{oversize}(t, L) = T_1(L)\dot{n}_{out}(t, L) \quad (5)$$

The separation functions $T_1(L)$ and $T_2(L)$ for the two screens are depicted in Fig. 3.

$$T_{1,2}(L) = \frac{\int_0^L exp\left(\frac{(L' - \mu_{1,2})^2}{2\,\sigma_{1,2}^2}\right) dL'}{\int_0^\infty exp\left(\frac{(L' - \mu_{1,2})^2}{2\,\sigma_{1,2}^2}\right) dL'} \quad (6)$$

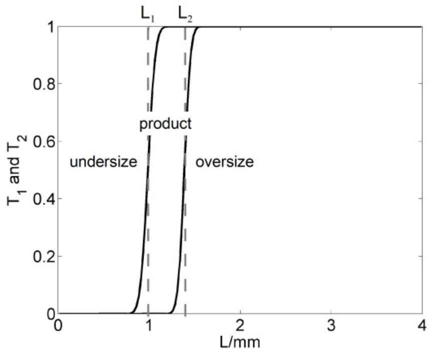

Figure 3. Separation functions $T_1(L)$ and $T_2(L)$ for the two screens

The particle distribution fed back from the mill is assumed to be a normal distribution $n_M(L)$ as shown in Fig. 4, where the mean diameter μ_M represents the mill grade. The particle flux from the mill is given by

$$\dot{n}_{mill}(t, L) = \frac{n_M(L)}{\int_0^\infty L^3 n_M(L) dL} \int_0^\infty L^3 \dot{n}_{oversize}(t, L) dL \quad (7)$$

where

$$n_M(L) = \frac{6exp\left(\frac{(L - \mu_M)^2}{2\,\sigma_M^2}\right)}{\sqrt{2\,\pi}\pi\rho\sigma_M}. \quad (8)$$

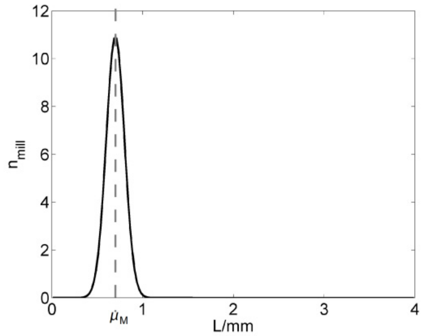

Figure 4. Particle size distribution of milled particles $n_M(L)$

The overall population balance equation thus reads

$$\frac{\partial n}{\partial t} = -G\frac{\partial n}{\partial L} - \dot{n}_{prod} - \dot{n}_{oversize} + \dot{n}_{mill}. \quad (9)$$

Assuming an ideal mass controller the drain K guaranteeing a constant third moment can be directly calculated.

$$K = -\frac{\int_0^\infty L^3 G\frac{\partial n}{\partial L}dL}{\int_0^\infty L^3 \dot{n}_{prod}dL} \quad (10)$$

As has been shown in [2] the qualitative dynamical behavior of the fluidized bed spray granulation with external product classification strongly depends on the process parameters especially the mill grade μ_M. For sufficiently high mill grade, transition processes decay slowly and the particle size distribution reaches as stable steady state. Decreasing the mill grade below a critical value results in a loss of stability and gives rise to nonlinear oscillations. As has been shown in [3,4] using the second moment of the particle size distribution μ_2 as the controlled variable and the mill grade μ_M as the control input a stabilization of the given process configuration is possible. In addition, good closed loop performance can be achieved for a well-tuned controller. In order to design PI or PID controllers, which can be easily implemented in a standard process control system, early lumping approaches in combination with an additional model reduction step have been investigated in [7]. In the following, it will be assumed that a PI controller $K(s)$ with $K_P = 8$ and $K_I = 0.1$ has been derived for a given nominal plant model at a certain set-point.

$$K(s) = K_P + K_I\frac{1}{s}, \quad (11)$$

In order to compensate for the very high plant gain, the second moment of the particle size distribution μ_2 is of the order of 10^7 and the mill grade μ_M is of the order of 10^{-1}, an additional gain $\frac{1}{K_s}$ has been introduced at the plant input μ_M with $K_s = 5 \cdot 10^{-7}$. The overall control scheme is shown in Fig. 5, where $\mu_{M,0}$ is the mill grade associated with the desired steady state particle size distribution.

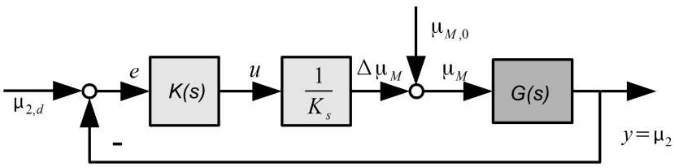

Figure 5. Overall control scheme

Applying the proposed controller at a set-point of $\mu_{2,d} = 5.1 \cdot 10^7$ for a step change in reference of $1.02 \cdot 10^5$ results in the transients depicted in Fig. 6.

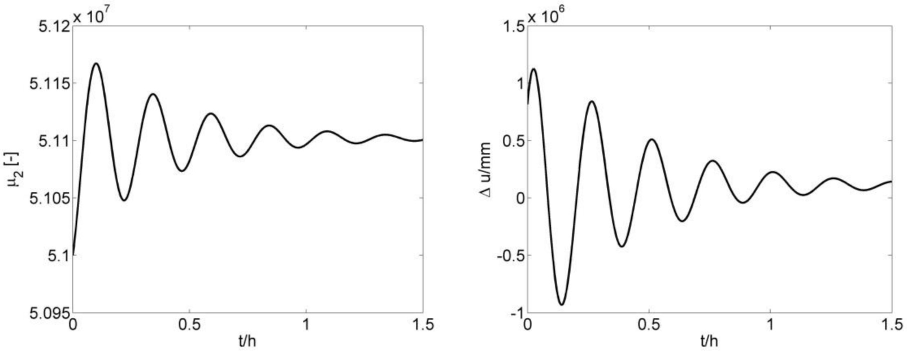

Figure 6. Closed loop response to a step change in reference – controlled variable $\mu_2(t)$ (left) and control variable $\Delta u(t) = \mu_M(t)$ (right)

As can be seen the transients in the second moment of the particle size distribution and the control input are weakly damped and the overshoot is relatively high. It is import to realize, that this undesired deterioration in closed loop control performance or even a loss of stability are hard to avoid in real fluidized bed spray granulation process due to

- Unforeseen changes in process condition, e.g. variation in drying conditions or variations in the feed concentration,
- Unconsidered changes in the reference set-point,
- Occurrence of additional effects, e.g. agglomeration or nucleation,
- Modelling errors or model uncertainties.

Therefore, in the next section an auto-tuning method is investigated allowing an automatic controller tuning on the real plant.

3. Iterative feedback tuning

As has been shown in the previous section model uncertainties and changes in the set-point may lead to a serious deterioration of the closed loop control performance. Hence, in the following iterative feedback tuning [8,9] as an approach for controller auto-tuning will be investigated. Here, the controller gains K_P and K_I will be used as tuning parameters. The closed loop controller performance will be reflected by a typical quadratic value function J, where Q weights the control error $e(t)$ and R weights the control input $u(t)$.

$$J = \frac{1}{T_f} \int_0^{T_f} e^T Q e + u^T R u \, dt \tag{12}$$

As has been depicted in Fig. 7 (left) this value function will be evaluated for a predefined experiment, here the response to a reference step, over a given time T_f. In order to minimize the value function J and therefore improve the closed loop control performance the following parameter update rule will be used,

$$p_{k+1} = p_k - \gamma \, H_k^{-1} \frac{\partial J}{\partial p_k} \tag{13}$$

where $p_k = \begin{bmatrix} K_P \\ K_I \end{bmatrix}$ is the vector of controller gains at time step t_k and the derivative of the value function with respect to the parameter vector p_k, i.e. $\frac{\partial J}{\partial p_k}$ is given by

$$\frac{\partial J}{\partial p_k} = \frac{1}{T_f}\int_0^{T_f} \frac{\partial e}{\partial p_k} Qe + \frac{\partial u}{\partial p_k} Ru \, dt \,. \quad (14)$$

Depending on the choice of the matrix H_k in eq. (13) different algorithms can be realized, e.g. choosing $H_k = I$ gives a gradient descent method. In this contribution H_k will be chosen as

$$H_k = \frac{1}{T_f}\int_0^{T_f} \frac{\partial e}{\partial p_k} Q \left(\frac{\partial e}{\partial p_k}\right)^T + \frac{\partial u}{\partial p_k} R \left(\frac{\partial u}{\partial p_k}\right)^T dt \quad (15)$$

which can be interpreted as an approximation to the Hessian of $J(p_k)$. It has to be mentioned, that both the first partial derivative (eq. 14) and the approximation of the Hessian of the value function (eq. 15) depend only on the two time signals $\frac{\partial e}{\partial p_k}$ and $\frac{\partial u}{\partial p_k}$. It can be shown, that both signals can be generated using the error signal $e(t)$, which results from the predefined experiment, as an input and augmenting the control scheme by an additional filter $\frac{\partial K(s)}{\partial p_k}$, i.e. the derivative of the controller transfer function with respect to the controller gains p_k.

$$\frac{\partial E(s)}{\partial p_k} = -\frac{\partial K(s)}{\partial p_k} \frac{G(s)}{1+G(s)K(s)} E(s) \quad (16)$$

$$\frac{\partial U(s)}{\partial p_k} = -\frac{\partial K(s)}{\partial p_k} \frac{1}{1+G(s)K(s)} E(s) \quad (17)$$

The configuration for the experimental evaluation of the signals $\frac{\partial e}{\partial p_k}$ and $\frac{\partial u}{\partial p_k}$ has been shown in Fig. 7 (right), here $e(t)$ is the error signal recorded from the previous experiment and no reference change occurs. The additional filter $\frac{\partial K(s)}{\partial p_k}$ is given by

$$\frac{\partial K(s)}{\partial p_k} = \begin{bmatrix} 1 & \frac{1}{s} \end{bmatrix}. \quad (18)$$

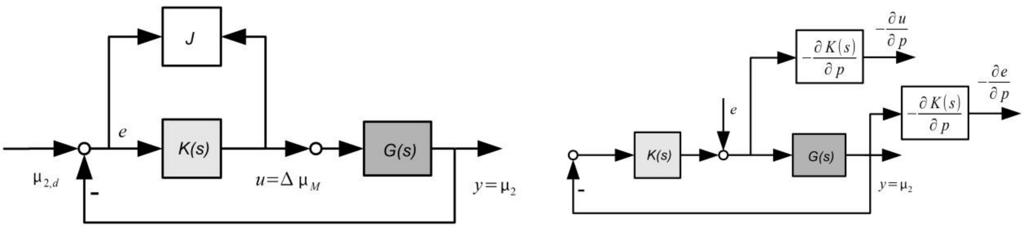

Figure 7. Experimental evaluation of the value function $J(p_k)$ and the error signal $e(t)$ (left) and experimental evaluation of the signals $\frac{\partial e}{\partial p_k}$ and $\frac{\partial u}{\partial p_k}$ (right)

4. Results

Applying the proposed iterative feedback tuning scheme to the fluidized bed spray granulation process with external product classification results in a considerable decrease of the value function J after already 3 iterations as shown in

Fig. 8 (left). This has been mainly achieved by increasing the K_P gain of the controller while slightly decreasing the K_I controller gain as depicted in Fig. 8 (right). As shown in Fig. 9 (left) the response to a reference step has less overshoot and the damping has been increased significantly. In addition, the control input decays much faster (Fig. 9 (right)).

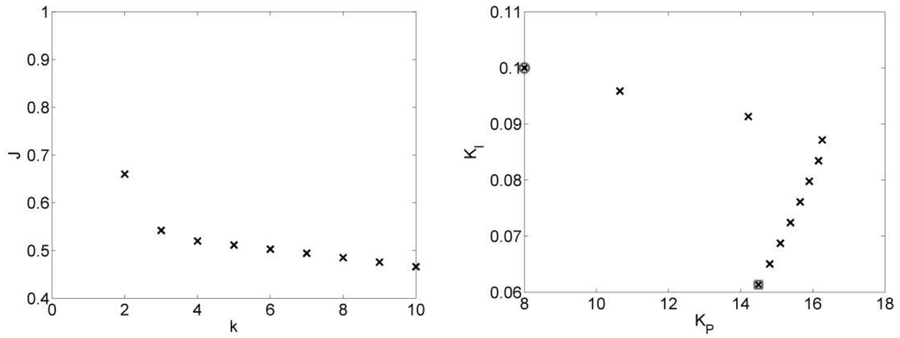

Figure 8. Value function $J(t_k)$ (left) and controller gains (right)

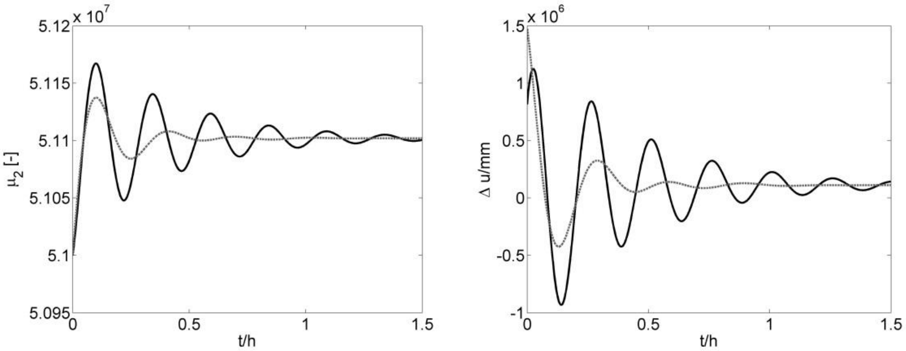

Figure 9. Closed loop response to a step change in reference before (solid black) and after tuning (dashed gray) – controlled variable $\mu_2(t)$ (left) and control variable $\Delta u(t) = \mu_M(t)$ (right)

5. Conclusion

In this contribution controller auto-tuning for continuous fluidized bed spray granulation processes with external product classification has been studied. It has been shown that the iterative feedback tuning method gives a practical and simple way to tune simple PI controllers on the real granulation process guaranteeing closed loop stability and performance in the presence of model uncertainties and other mismatches.

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