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Discrepancy based control of particulate processes

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ABSTRACT

This article deals with a new approach to particulate process control. The model system under investigation, the continuous fluidized bed spray granulation with external product classification, is described by a nonlinear partial integro-differential equation, the population balance equation for the particle size distribution. This process exhibits interesting dynamical behavior, i.e. a change of the stability behavior and the occurrence of limit cycles. In addition, the zero dynamics with respect to moment measurements frequently used in practice are unstable in certain parameter regions. In order to stabilize these types of systems in this contribution the use of a generalized distance measure, the discrepancy, is proposed. Applying, the associated stability theory, i.e. stability theory with respect to two discrepancies, a stabilizing control law can be derived. One of the main advantages of the proposed discrepancy based control method is that no model reduction is required.

1. Introduction

Control of distributed parameter systems (e.g. [1–3]) and particulate processes in particular is an active field of research. From a control theory point of view particulate processes or processes described by population balance models are of great interest. This is due to the fact that the population balance equation, depending on the specific process, may be a nonlinear partial integro-differential equation with sinks and sources in the domain. So far, control approaches for particulate processes reported in the literature can be roughly divided into linear (e.g. [4–6,26]) and nonlinear (e.g. [7]) approaches using a lumped model, resulting from discretization (e.g. [4–6,26]) or the method of moments (e.g. [7]). Applying linear infinite dimensional H_∞-control theory (e.g. [8,9]) an infinite dimensional control law can be derived, which has to be lumped for implementation reasons. In this contribution a new nonlinear control approach will be presented, which enables a direct control design and a straight forward implementation. It has been recently applied by the authors to the problem of stabilization of continuous crystallization processes [10] and fluidized bed spray granulation with internal [11,12] and external product classification [12,13]. However, there focus has been on stability with respect to two discrepancies only. Therefore, the main contribution of this paper is the connection between pointwise convergence, i.e. convergence in a L_∞-norm, and stability with respect to two discrepancies and the extension to systems with unstable zero dynamics.

The paper is organized as follows: in Section 2 the model system, a continuous fluidized bed spray granulation with external product classification, is introduced. In Section 3 stabilization of a general population balance model in the sense of the L_2-norm is investigated in order to clarify the problems of conventional approaches and motivate the introduction of a generalized distance measure called discrepancy. In Section 4 the main theoretic concepts of stability with respect to two discrepancies are stated. The connection between stability with respect to two discrepancies and stability in the sense of the L_∞-norm is outlined in Section 5. In Section 6 the discrepancy based control method is applied in order to derive a stabilizing control law for the model system. Some final remarks conclude the paper.

2. Fluidized bed spray granulation

Granulation is an important class of production processes in food, chemical and pharmaceutical industries. It is used to produce granules from liquid products, e.g. solutions or suspensions. More and more frequently, granulation is combined with fluidized bed technology. Here, a fluidized bed is formed from solid particles under appropriate conditions, e.g. by passing a gas or liquid through the solid material. Important properties of the fluidized bed are the fluid like behavior, an enlarged active surface caused by increased bed porosity and good particle mixing. In addition, fluidization technology allows a combination of different processes like drying, coating, mixing, granulation, agglomeration, heating or pneumatic transport [14].

In Fig. 1 a typical process flow sheet is shown. The granulator consists of a granulation chamber, where the particle population

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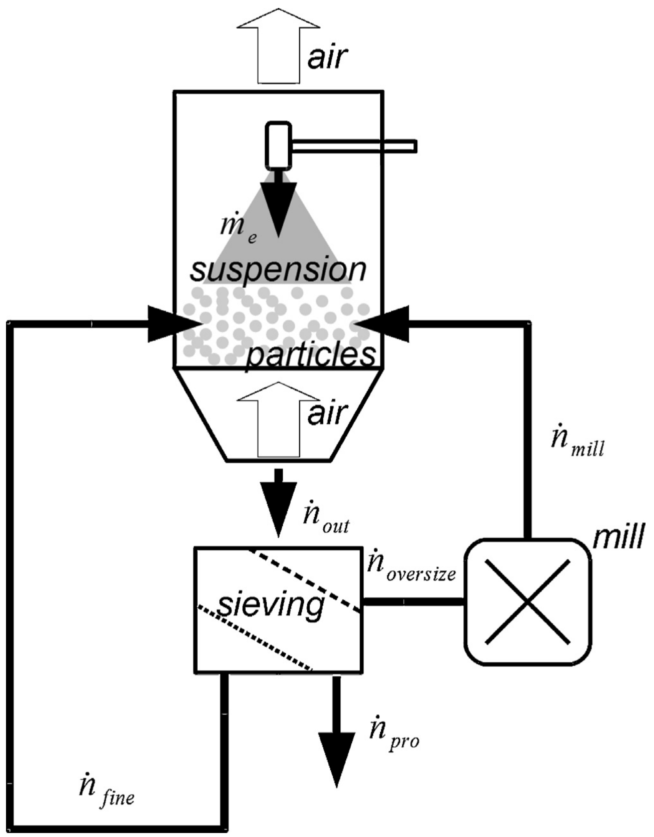

Fig. 1. Process scheme.

having a specific particle size distribution $n(t, L)$ is fluidized through an air stream. Here, $t \geq 0$ is the time and $L \geq 0$ the characteristic particle size. Injecting a solution or suspension with an effective mass flow rate $\dot{m}_e$ the particles are then coated, i.e. the liquid settles on the particles surface and dries. In the continuous configuration with external product classification a certain part of the solid particles is removed from the granulation chamber and separated in a seeding box into three classes

(1) product particles, i.e. particles being in the desired size range,
(2) fine particles, which are directly fed back to the granulation chamber,
(3) oversized particles, which are grinded in a mill and fed back to the process.

Assuming ideal mixing a population balance model for the particle size distribution $n(t, L)$ has been derived in [14]. In addition, it is supposed that other kinetic processes, such as internal and external nucleation, agglomeration, particle breakage and attrition, can be neglected. The resulting model consists of the following particle fluxes

- $\dot{n}_{prod}$ particle flux due to product removal,
- $\dot{n}_{oversize}$ particle flux due to oversize removal,
- $\dot{n}_{mill}$ particle flux due to particles fed back from mill.

The flux of fine particles can be omitted as fine particles are directly fed back to the granulator resulting in a cancellation of the associated sink and source terms. The population balance model and its boundary conditions thus are

$$\frac{\partial n}{\partial t} = -G\frac{\partial n}{\partial L} - \dot{n}_{prod} - \dot{n}_{oversize} + \dot{n}_{mill}, \quad (1)$$

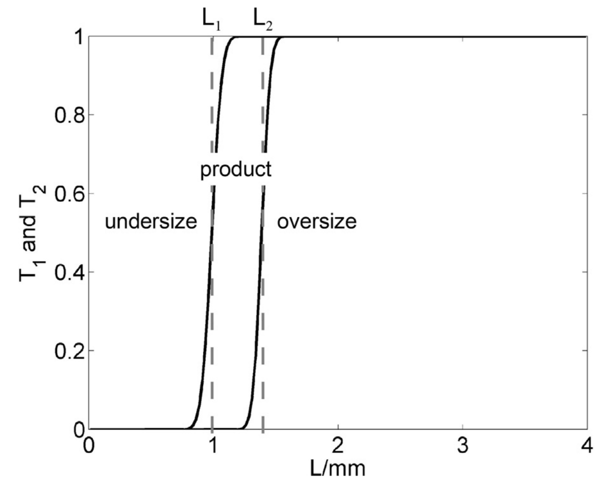

Fig. 2. Separation functions T_1 and T_2.

$$n(t, 0) = 0, \quad (2)$$

$$\lim_{L\to\infty} n(t, L) = 0, \quad (3)$$

where G is the particle growth rate. Assuming spherical particles and size independent growth the growth rate G is

$$G = \frac{2\dot{m}_e}{\varrho A} = \frac{2\dot{m}_e}{\varrho \pi \mu_2}, \quad (4)$$

where ϱ is the particle density, A is the overall particle surface and $\mu_2 = \int_0^\infty L^2 n dL$ the second moment of the particle size distribution. In the continuous configuration of the fluidized bed spray granulation particles are continuously removed in order to achieve a constant bed mass, which correlates to a constant third moment of the particle number distribution $\mu_3 = \int_0^\infty L^3 n dL$. The particle flux being removed from the granulator is

$$\dot{n}_{out} = Kn \quad (5)$$

where K is the drain, which follows from the assumption of a constant bed mass and is derived later. The removed particles are then sieved in two sieves and separated into the three classes fine, product and oversize

$$\dot{n}_{fines} = (1 - T_2(L))(1 - T_1(L))\dot{n}_{out} \quad (6)$$

$$\dot{n}_{prod} = T_2(L)(1 - T_1(L))\dot{n}_{out} \quad (7)$$

$$\dot{n}_{oversize} = T_1(L)\dot{n}_{out}. \quad (8)$$

Here, the separation functions $T_1(L)$ and $T_2(L)$ for the two screens depicted in Fig. 2 are as follows

$$T_k(L) = \frac{\int_0^L e^{-((L\prime - L_k)^2/2\sigma_k^2)} dL\prime}{\int_0^\infty e^{-((L-L_k)^2/2\sigma_k^2)} dL} \quad k = 1, 2. \quad (9)$$

The shape of the particle distribution fed back from the mill n_{mill} is assumed to be a normal distribution, where the mean diameter μ_M represents the mill grade

$$n_{mill} = 6\frac{e^{-((L-\mu_M)^2/(2\sigma_M^2))}}{\sqrt{2\pi}\pi\varrho\sigma_M} \quad (10)$$

The particle flux from the mill is then given by

$$\dot{n}_{mill} = \frac{n_{mill}}{\int_0^\infty L^3 n_{mill} dL}\int_0^\infty L^3 \dot{n}_{oversize} dL, \quad (11)$$

where the third moment of n_{mill} accounts for mass conservation in the mill. In the following, the mill grade μ_M will be used as the