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Variable-structure PID controller for level process

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ABSTRACT

A variable-structure (VS) PID controller for the level process is proposed. A methodology of analysis of its stability and performance is given. It is proposed that stability of the VS system can be approximately analyzed via the describing function method. The describing function of the VS PID controller is derived. It is shown that the system with the VS PID controller is quasi-linear. Tuning rules for the VS PI controller for the level process are given. It is shown via the theory and simulations presented that, if properly tuned, the VS PI controller has higher performance than the conventional PI controller for the process considered.

1. Introduction

Liquid level control in various tanks and vessels is one of the most common controls in the process industry. It can usually be categorized into (a) the process control in which maintaining the level to a certain set point is the primary objective (boiler steam drums, bottom-product and reflux drums of distillation columns — just to name a few), and (b) the control in which large level fluctuations are allowed and even assumed — the case of so called surge vessels which accumulate feedstock from one or more sources and deliver a smooth feed rate. In the latter case the primary control objective is the outflow stabilization. In the present paper, only the first category of level control objectives will be considered.

Normally level is controlled by a PI or PID controller, which can be implemented as a part of a distributed control system or locally. The controllers are tuned in accordance with established methods and techniques (Astrom & Hagglund, 1984,1995; Shinskey, 1988; Ziegler & Nichols, 1942). However, in many situations satisfactory performance can hardly be achieved. This happens due to the fact that level process is an integrating process, which in combination with the integral term of the PI/PID controller results in a double integrator in the loop. The presence of the controller integral term is absolutely necessary to ensure zero error in a steady state, and the use of a PI controller in combination with an integrating process usually results in oscillatory transients having low damping. In summary, level process is not as easy to control in terms of providing a good performance as it might seem.

PID controllers are used more seldom for the considered process than PI controllers because the performance improvement due to introduction of the derivative term is marginal while the derivative term would amplify the measurement noise. Therefore, in the application part of this paper our analysis and design are limited to the case of PI controllers. Yet, the use of a PID controller would differ from the presented analysis only by the tuning rules applied.

The variable-structure (VS) control was proposed a few decades ago and was mainly developed as a sliding mode control (Utkin, 1992). There are a number of controllers described in the literature under the name of “variable-structure PID” controllers, which, however, define a few different types of control. Let us use the term “variable-structure” understanding it as a type of the switching control in which switching occurs when the state trajectory moves from one region of the partitioned state space to another — as it was described in Utkin (1992). The sliding mode may or may not occur — in dependence on the designed switching strategy. Therefore, the following properties of the variable-structure system are assumed. *A. It is a switching type of control* (*can also be viewed as parameters of the controller being changed in a discontinuous manner*). *B. The controller switching happens in dependence on the value of the state vector. C. The state space is partitioned into a few regions corresponding to a few different controllers, so that i-th controller is selected when the current value of the state vector belongs to the i-th region.*

It should be noted that various switching strategies are widely used in the control engineering practice. However, most of them are not variable-structure (VS) controllers — considering the features given above. The switching usually is organized to provide better performance under varying parameter conditions, which is not much different from the gain-scheduling strategy

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that has been used in practice for decades. Most of the described VS PID controllers utilize a certain switching strategy between a few different PID controllers or continuous change of controller parameters. A continuous change of controller parameters in dependence on the parameters of the input signal is used in Mainardi, Mantovani, Fabbri, and Bonfe (2003). Also, a continuous change of the parameters of the PID controller by neural/fuzzy logic (so that in certain modes the integral gain becomes zero) is proposed in Chen and Chang (1995). In Ismail and Bedwani (2001), Suyitno, Fujikawa, Kobayashi, and Dote (1993), a continuous change of the PID controller parameters is carried out by a fuzzy logic and a genetic algorithm, respectively, to optimize the transient tracking performance. In Balestrino, Biagini, Bolognesi, and Crisostomi (2009), a continuous change of the PID controller parameters is proposed, so that it becomes in fact the controller with nonlinear gains for every control component, which is similar to Shinskey (1988). A VS PID controller with a sliding mode is proposed in Jafarov, Parlakci, and Istefanopulos (2005), in which the proposed control is, in fact, a combination of an integral sliding mode and a conventional PID controls. In the paper (Hodel & Hall, 2001) and subsequent discussion offered in Hodel and Hall (2004) and Mantz and Battista (2004), a VS PID controller for counteracting the integral windup is proposed. The switching between the two controller structures is based on the comparison of the signals before the limiter (saturation nonlinearity) and after the limiter. In Qiu, Yuan, and Wang (2006), a VS PID controller with switches between P, PD and PID structures in dependence on the error magnitude was reported as beneficial for reactor temperature control. Similar design was used in Zhang et al. 2010 to improve dynamics of positioning of a telescope.

The brief overview given above shows that most of the controllers that are called VS PID are in fact not variable-structure systems (paper by Jafarov et al. (2005) is an exception) but different types of switching control logic or continuously changed controller parameters. In the present paper, a VS controller, in which switching between a few PID controllers occurs in dependence on the state vector value, is proposed. Switching strategy of this controller is in agreement with the definition of the VS system: see Utkin (1992) and comments above. The proposed switching strategy does not account for the changes of the plant (process) parameters. Instead, it assumes constant parameters of the process but provides a type of nonlinear control that allows for the enhancement of the system performance (in comparison with a conventional PID control) via exploiting nonlinear features of the control. It should be noted that the proposed controller does not generate a SM in the system despite the fact that it is a VS controller.

Another distinction of the present results from the references given above is that the proposed VS control leads to a solid controller design methodology based on the process model. The design methodology of the VS PI controller is presented. The objective of this paper is, therefore, to develop a VS PI controller for the level process and a methodology of its parameters design or tuning.

The paper is organized as follows. At first the model of a PI-controlled level process disturbed by flow change is considered. Then the describing function analysis is carried out for VS PID controller, and stability analysis is given. In the following section, the dynamics of the level loop having valve dynamics is analyzed. After that, tuning rules for a VS PI controller for level process are provided. And finally, a simulation example is given.

2. Simplified model of level process and VS principle

The model of the level process can be schematically represented by a tank, which has a controlled inflow and uncontrolled outflow (Fig. 1). In many cased the actual arrangement is the opposite: the inflow is uncontrolled, and level control is done via manipulating the outflow. Yet, the second situation can be transformed into the first one via changing the flow signs.

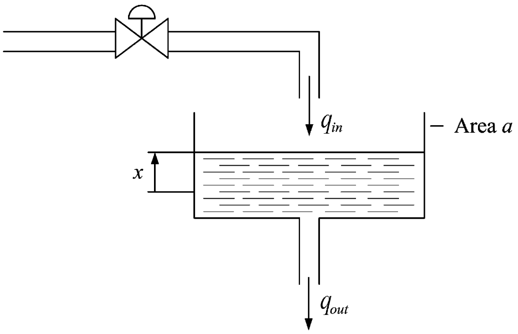

Fig. 1. The tank level process.

Let us assume that inflow can manipulated through some linear dynamics, so that in a steady state the inflow is proportional to the controller command. (Note: in practice, the valve opening is usually proportional to the controller command, but the flow is not necessarily proportional to the controller command and also depends on the upstream pressure. However, this dependence can be linearized by the use of the flow controller cascaded with the level controller, for example.)

Write the equation of the process.

$$\dot{x}_1 = \frac{1}{a}(q_{\text{in}} - q_{\text{out}}) \tag{1}$$

where x_1 is the level value, q_{in} is the controlled flow to the tank, q_{out} is the uncontrolled flow from the tank, a is the cross-sectional area of the tank (it is assumed the tank has such geometry that a is constant).

Let the process be controlled by a PI controller given by the following equation in the Laplace domain.

$$u(s) = K\left(1 + \frac{1}{Ts}\right)e(s) \tag{2}$$

where u is control, K is the controller proportional gain, T is the controller integral time constant, s is the Laplace variable, e is the error (the difference between the level set point and the actual level value).

At this point, let us consider that the control u produced by the controller is equal to the inflow (no actuator-valve dynamics): $q_{\text{in}} = u$, that the outflow is zero, and that the set point value is zero, so that $e = -x$. Rewrite Eqs. (1) and (2) in the normal form:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\frac{K}{Ta}x_1 - \frac{K}{a}x_2 \end{cases} \tag{3}$$

Get rid of time in (3) via dividing the second equation by the first one and obtain the equations of the state trajectories.

$$\frac{dx_2}{dx_1} = -\frac{K}{a}\left(\frac{1}{T}\frac{x_1}{x_2} + 1\right) \tag{4}$$

Depending on the parameters K and T of the controller, Eq. (4) can represent either an underdamped (oscillatory) process (Fig. 2) or an overdamped process (Fig. 3), with the origin being focus or node, respectively.

To analyze advantages and drawbacks of each of the presented controllers with respect to the level control process, let us define the control objectives. First, level controller is a regulator: the set point is usually constant; the main objective of the controller is to attenuate (reject) possible disturbances. Second, the only possible disturbance is the change of outflow. This change is often an abrupt change due to connection or disconnection of consumers.