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Disturbance-observer Based PID Control Design for a Level Control System with Valve Stiction

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Abstract: This paper considers the combination of disturbance observer (DOB) design with the conventional PID controllers to improve the ability to compensate effects of valve stiction. In the proposed method, the process delay is firstly approximated to a high-order transfer function using Pade approximation. Then an additional low-pass filter is designed to cope with the nonminimum-phase characteristic of the approximated process. Therefore, a DOB with a specific structured is constructed to estimate the dynamic of valve stiction on the system output. A numerical example is provided to demonstrate the benefit of the proposed approach.

Keywords: Valve Stiction, PID Control, Compensation, Disturbance Observer, Pade Approximation, Low-pass Filter

1. INTRODUCTION

Control valves are one of the most common equipment in industry process. Problems with control valves can arise in several manners. One of important problems is the valve stiction [1], [2], which causes nonlinearity in control loops and thus leads to performance degradation in performances of process control systems. Therefore, compensation of the valve stiction is important to improve control system performance and ensure tight product quality in industrial control systems. Study in this area has thus received increasing attention in both academic and industry.

Several researches on valve stiction compensation have been considered in the literature in the past two decades. Simple stiction compensation approaches which is applied to the one-parameter stiction model have been proposed in [3] and [4]. Another approach based on analyzing oscillations caused by valve stiction has been considered in [7]. This approach is still relied on a trial-and-error tuning of controller parameters. More advanced control strategies such as model predictive control and sliding mode control have been considered in [5] and [6], respectively, for the stiction compensation. However, such control approaches result in controllers with complicated structures, and might be difficult for practical implementation.

Motivated by the research of [14], this paper proposes an alternative approach for the valve stiction compensation. The current approach firstly considers the dynamic of valve stiction as a disturbance with unknown characteristics, then design a disturbance observer (DOB) [11], [12] to reject effects from the disturbance. When the process contains a delay, however, the design of a DOB is much more difficult than that for a process without delay. This issue can be addressed by approximation of the process delay to a high-order transfer function using Pade approximation, then design an additional low-pass filter so called V-filter [15] to cope with the nonminimum-phase characteristic of the approximated process. We perform experiments to show that combination of the designed DOB with a typical PID controller can make the closed-loop system effectively track a set point, even under a situation of high stiction of the valve.

2. PROCESS CONTROL SYSTEM WITH VALVE STICTION

Consider a feedback control system for an industrial process depicted in Fig. 1, where the valve represents the actuator in the control loop. The variables r, e, v, u, y denote respectively the setpoint, the tracking error, the controller output, the process input, and the process output. In this paper, the controller $K(s)$ is chosen as a standard PID controller. In fact, PID control is the simplest and the most used control strategy for process control systems. The process $P(s)$ is described by a linear system with time-delay in Eq. (1):

$$P(s) = P_0(s)e^{-\theta s}, \tag{1}$$

where $P_0(s)$ is a 2nd- order transfer function, and θ is the time delay of the process.

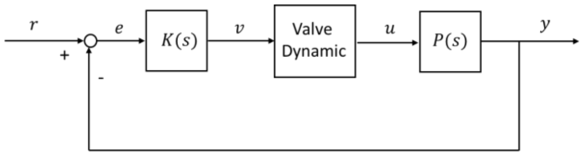

Fig. 1. A feedback control loop regulated by a valve.

Modeling valve stiction, according to [16], aims to determine the relationship between valve input, i.e., controller output and valve output. The two primary categories into which the current models of valve stiction are divided are physical model and data-driven model [8]. The mechanisms of the valve can be explained by the physical model. Due to the existence of numerous unidentified valve parameters, however, it is difficult to model the actual valve properties [9]. On the

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other hand, the data-driven model is developed using actual industrial data as well as an input-output study of sticky valves. With fewer factors, it offers a more straightforward way for modeling valve stiction.

Moreover, without having a lot of prior physical information, the nonlinear valve moving mechanism can be explained. There have been several data-driven stiction models presented. A one-parameter valve stiction model was suggested by Stenman et al. in [17], however in some circumstances, it was unable to reflect the true characteristics of the stiction event. The Stenman model was modified by Choudhury et al. in [10], and they suggested a two-parameter model that includes the two parameters S and J. Because the parameters are linked to valve frictions, the model offers a solid explanation for the physical mechanism of valve stiction.

A typical input-output relationship of a sticky valve is represented in Fig. 2. The stiction behavior consists of three parts including dead band, stick band and slip jump. In general, stiction exhibits the features of hysteresis and dead band, and hence can be considered as a nonlinearity in the control loop.

According to description of the S-J valve stiction model, the parameter S and J have some relationships with valve frictions features, that is, $S = f_s + f_d$ and $J = f_s - f_d$, where f_s and f_d are the maximum static friction and maximum kinetic friction of the valve, respectively. It is notable that these relationships can represent the actual characteristics of valve stiction [10].

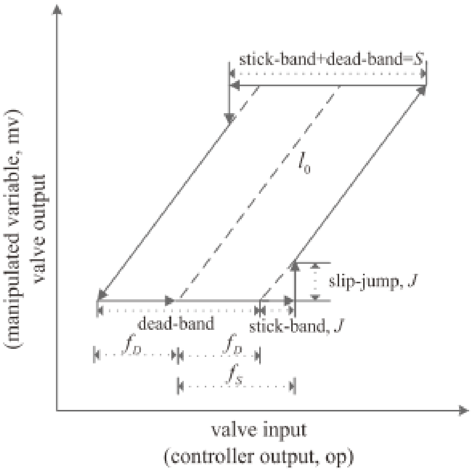

Fig. 2. Typical input-output relationship of a sticky valve [14].

3. DISTURBANCE OBSERVER DESIGN

Motivated by the approach of [14], the dynamic of the valve stiction is considered as a disturbance in the control system. Therefore, the control loop with valve stiction can be equivalently represented in Fig. 3, where d is the disturbance.

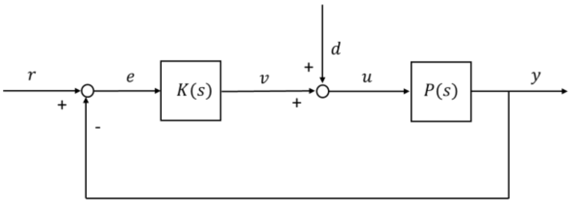

Fig. 3. A feedback control loop with a disturbance.

A well-known strategy to handle the disturbance in the control loop is to construct a disturbance observer (DOB). The block diagram of a classical DOB is shown in Fig. 4 [11], [12]. The transfer function $P_n(s)$ represents the nominal process of the actual process $P(s)$, and $Q(s)$ is a low-pass filter so called Q-filter whose transfer function is in the following form [11]:

$$Q(s) = \frac{\sum_{i=0}^{n} \binom{m}{i} (\tau s)^i}{(\tau s + 1)^m} \tag{2}$$

where τ is the filter parameter, and the order of the filter is determined by the positive integers n and m with $m \geq n$.

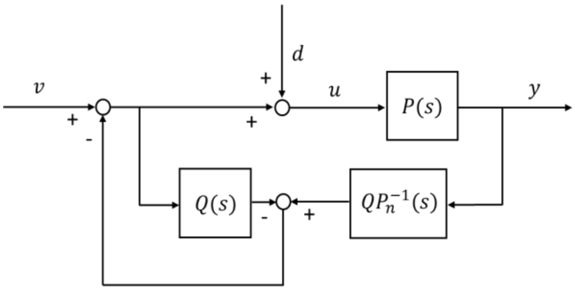

Fig. 4. Block diagram of a classical DOB.

Stability of $P_n^{-1}(s)$ is very crucial in the design of a DOB. If $P_n(s)$ is non-minimum phase, the control system with the classical DOB tends to instability because the poles of the internal systems locate in the right half plane [13]. In order to overcome the stability issue of the DOB, Son et al. [15] propose a modified DOB with a more complicated structure depicted in Fig. 5. The main feature of a modified DOB is that an additional filter $V(s)$ is constructed so that the transfer function $P_n(s) + V(s)$ is minimum phase, and thus $(P_n + V)^{-1}(s)$ is stable.

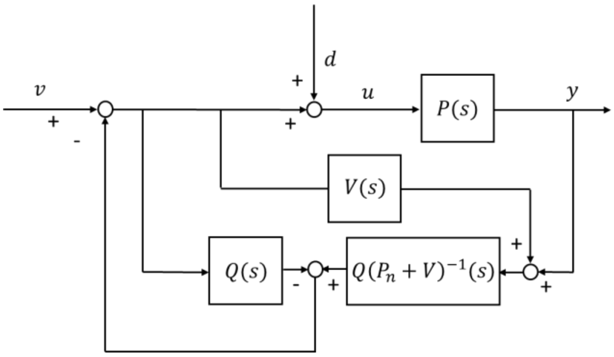

Fig. 5. A modified DOB with an additional filter.

In Fig. 5, the output y can be expressed in terms of the controller output v and the disturbance d as

$$y = \frac{P(P_n+V)}{(P_n+V)(1-Q)+(P+V)Q} v$$

$$+ \frac{P(P_n+V)(1-Q)+PVQ}{(P_n+V)(1-Q)+(P+V)Q} d.$$

It can be seen from the above expression that if $Q \approx 1$ and $V \approx 0$ in the low frequency range, then the effects of the disturbance d disappear, and thus $y \approx P_n(s)v$. This implies that the DOB can be used as an inner-loop controller making the input-output property of the actual process approach to that of the nominal process in case of no disturbance.

It is not difficult to verify that if the controller $K(s)$ is a stabilizing controller, then $P(s)+K^{-1}(s)$ is a minimum phase system [15]. Thus, a possible choice of the V-filter is $V(s)=K^{-1}(s)$. Moreover, based on the above discussion, when $V(s) \approx 0$ for almost all the frequency range, the input-output behavior of $P(s)$ is approximately the same as that of $P_n(s)$ and thus $P_n(s)+V(s)$ is likely non-minimum phase.

4. NUMERICAL EXPERIMENTS

This section provides a numerical example to illustrate benefits of the proposed approach. All the experiments are executed in MATLAB 2022.

We firstly model the process by the system identification method. Input and output data are collected from the level process control plant in our laboratory. By employing the System Identification Toolbox to the collected input and output data, we obtain the following linear 2nd -order model with time delay for the plant:

$$P(s) = \frac{1.2631 \times 10^4 + 0.0747}{(7997.7s+1)\,(151.48s+1)} e^{-16s}$$

A PI controller is designed to stabilized the closed-loop system with good performances. By using Autotune function in MATLAB, the controller $K(s) = 0.8618 + \frac{0.002492}{s}$ is obtained.

Next, we assumed that the control valve is sticky where the characteristic is described by the S-J model. We then consider the following two types of DOBs for suppressing the effect of the valve stiction:

Type 1 DOB: We choose

$$P_n(s) = P_0(s) = \frac{1.2631 \times 10^4 + 0.0747}{(7997.7s+1)\,(151.48s+1)}$$

that is, the delay term e^{-16s} is approximated by 1. Because $P_n(s)$ is minimum phase, a classical DOB is applicable in this case.

Type 2 DOB: We choose

$$P_n(s) = P_0(s)P_2(s)$$

where $P_2(s)$ is the 2nd-order Pade's approximation of e^{-16s}, i.e., $P_2(s) = \frac{3-24s+16s^2}{3+24s+16s^2}$. It is obvious that $P_n(s)$ is non-minimum phase in this case, thus a modified DOB with a V-filter is necessary.

We perform numerical experiments with several values of the parameter (S, J) to test the performance of the two types of DOBs above, which is measured in terms of the integral absolute error (IAE) of the closed-loop system. The results are summarized in the following tables:

Table 1 IAE values obtained from Type 1 DOB

S/J	0.1	0.3	0.5
1	2464	2295	2273
1.2	2824	2298	2269
1.4	3400	3463	2266
1.6	25100	3436	3463
1.8	27600	25100	4068
2	30200	27600	25100

Table 2 IAE values obtained from Type 2 DOB

S/J	0.1	0.3	0.5
1	204.8	204.8	204.9
1.2	203.8	204.8	204.8
1.4	203.9	204.2	204.9
1.6	202.8	203.9	205
1.8	202.8	202.8	204.2
2	202.8	202.8	202.8

We observe from the tables above that the IAE values obtained from Type 2 DOB are significantly improved from those obtained from Type 1 DOB. The improvement is more apparent when the parameters S and J become larger. It can be concluded from the numerical results that a modified DOB with V-filter is more suitable to reduce the effect of the valve stiction.

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