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Research article

Dominant root locus in state estimator design for material flow processes: A case study of hot strip rolling

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ABSTRACT

The purpose of the paper is to achieve a constrained estimation of process state variables using the anisochronic state observer tuned by the dominant root locus technique. The anisochronic state observer is based on the state-space time delay model of the process. Moreover the process model is identified not only as delayed but also as non-linear. This model is developed to describe a material flow process. The root locus technique combined with the magnitude optimum method is utilized to investigate the estimation process. Resulting dominant roots location serves as a measure of estimation process performance. The higher the dominant (natural) frequency in the leftmost position of the complex plane the more enhanced performance with good robustness is achieved. Also the model based observer control methodology for material flow processes is provided by means of the separation principle. For demonstration purposes, the computer-based anisochronic state observer is applied to the strip temperatures estimation in the hot strip finishing mill composed of seven stands. This application was the original motivation to the presented research.

1. Introduction

The observers for non-linear systems are Lyapunov-based estimators in general, e.g. [1] and references therein. The observers designed for non-linear systems having triangular structure are presented in [2,3]. Next, for fuzzy systems the observer is designed recently in [4–7] and for stochastic systems in [8–11]. As regards time delay systems there are numerous works designing observers, for instance [2,12–16]. To achieve global asymptotic stability the Lyapunov-Krasovskii functional approach is usually applied [2,14]. Frequently the Lyapunov-based observer designs utilize linearization techniques, [9,17]. These techniques are applied to Extended Kalman Observer (EKO) designs in which the Lyapunov-type constraints lead to Linear Matrix Inequalities (LMIs) problem. In addition relaxed LMI-based designs are desirable for observer-based control in general [4]. In case of Takagi-Sugeno models the relaxation of the LMI conditions to the observer design is obtained by means of an intermediate variable [6]. In [7] the relaxed LMI conditions are achieved by means of additional variables and multiple matrices. A model-free approach to an observer design for fault diagnosis is a data-driven approach to the observer design for faulty processes whose analytical models are unavailable [18]. The LMI-based designs are frequently combined with H_∞ method, e.g. [16,19]. Next to the convenient performance indices like H_∞ and H_2 the admissible Lipschitz constant or disturbance attenuation level are optimized, too [16]. The Lyapunov-based observers are directly obtained by sliding mode approach [20–23]. In [23] a paradigm to sliding mode observer based control design for non-linear systems with time varying delay is developed.

Once the process transient response is characterized by a distributed parameter that can be approximated by a delay distribution the process with distributed delay is dealt with. This process can be described by an anisochronic process model developed in [24]. A specific feature of the anisochronic state model is its infinite spectrum. Despite this the model can satisfy the requirement of spectral observability, [25], for the sake of observer design. Based on this model an anisochronic state observer is designed in which the process delays are cancelled within the process estimation [24]. Then, the meromorphic observer-based pole assignment applying the anisochronic state observer can provide a dominant pole placement in the control loop [26]. Another approach to locating the system dominant poles is the

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continuous pole placement developed by Michiels et al. [27], and later extended in [28]. On this pole placement approach the quasi-direct pole placement is based enabling to adjust much greater number of state feedback controller gains than the number of prescribed dominant poles [29]. Also the root locus technique is applied to the dominant pole placement for time delay systems in PID control loop [30].

The LMIs programming is capable to meet not only the Lyapunov-type constraints but also the pole placement requirements, well guaranteed for processes with finite spectrum [31]. Since the process spectrum is infinite as mentioned above the pole placement problem is extended to the problem of the dominant pole placement. Then the LMI programming capability is limited by the dominance requirement of the placed poles. In other words the dominant pole placement is preferred to the other constraints considered in, e.g. [31–33]. As a direct tool for this pole placement the dominant root locus is beneficially applied in the paper.

The aim of the paper is to design the anisochronic observer for non-linear systems with state delays guaranteeing global asymptotic stability. Since the global asymptotic stability turns out to be too conservative the local asymptotic stability is provided as the main result of the paper. The local asymptotic stability proof is based on the LMI approach. The universal design method is the dominant root locus that is novel in its application to the local asymptotic stability achievement. This paper is motivated by a practical problem of temperature estimation across the hot strip finishing mill which is shown in the case study example of the observer design. To the end the conclusion is given that this observer design is well applicable for material flow processes.

The paper is organized as follows: first the non-linear state space model with delays is introduced in Section 2. In Section 3 the anisochronic state observer is designed and its stability is investigated. In Section 4 the anisochronic state observer is tuned by the dominant root locus combined with the magnitude optimum method. In Section 5 the methodology to the anisochronic observer based control is provided and in Section 6 the case study of hot strip rolling process is presented. Finally the paper results are discussed in Section 7 and the paper is concluded in Section 8.

1.1. Notations

Throughout the paper the following notations are used:

- $\mathbf{A}^T$ is the transpose matrix of $\mathbf{A}$;
- $\mathbf{I}$ represents the identity matrix of appropriate dimension;
- $\mathbf{0}$ represents the null matrix of appropriate dimension;
- given a square matrix $\mathbf{P}$, the notation $\mathbf{P} > 0$ ($\mathbf{P} < 0$) means that this matrix is positive definite (negative definite);
- $(*)$ is used for the blocks induced by symmetry.

2. Nonlinear state space model of processes with delays

It is often the case in process industry that there is a rather higher number of process variables the knowledge of which is to be taken into account in the control strategy design but their measurement is not available. Only a limited set of process variable measurements is feasible and due to the absence of substantial part of process state variable knowledge the control design in these cases is lacking in sufficient amount of data on the process actual state. With regard to this discrepancy the usual control schemes based on immediate use of available measurements are impractical in this type of processes. One of the means to overcome this problem is an application of *state observer* estimating the unmeasured state variables from the available measurements and from the known process inputs. Particularly the state observer design for processes with delays makes possible to control these processes that are frequently in the industry.

Significant class of processes satisfying the above mentioned classification is the material flow processes. Considered model structure of the material flow processes is composed of Lipschitz non-linearities and time delays. As regards the process delays, φ_i, $i = 1, 2, \dots, n$, they are real and positive. Assume that the largest delay is denoted by Φ_m. Next, let the initial measurement for the process estimation that represents an input into the material flow process be x_0. Then x_0 cannot be included into the state vector given as follows

$$\mathbf{x} = [\, x_1, x_2, \dots, x_{n-1}, x_n]^T. \tag{1}$$

The other process inputs together with x_0 constitute the following input vector

$$\mathbf{u} = \left[x_0,\ \mathbf{u}_1^T, \mathbf{u}_2^T, \dots, \mathbf{u}_{n-1}^T, \mathbf{u}_n^T\right]^T. \tag{2}$$

In other words the variable number of inputs can enter every process section and then the following vector of process measurements is introduced

$$\mathbf{z} = \left[x_0, \mathbf{x}_{n-1}^T\right]^T = [\, x_0, x_1, x_2, \dots, x_{n-2}, x_{n-1}]^T. \tag{3}$$

To select the available measurements from all the process variables the output matrix determining the output variables is introduced as $q \times n$ matrix $\mathbf{C}$, $q < n$. On the basis of the above considerations, the following material flow process is described as follows

$$\frac{d\mathbf{x}(t)}{dt} = \mathbf{f}(\mathbf{x}, \mathbf{x}_\Phi, \mathbf{u}) \tag{4}$$

where $\mathbf{f}(.)$ is the non-linear right-hand side of (4) with state delays, $\mathbf{x} \in \Re^n$ and $\mathbf{u} \in \Re^m, m > n$. $\mathbf{x}_\Phi$ is the delayed state vector as follows

$$\mathbf{x}_\Phi = \left[x_1(t-\varphi_1), x_2(t-\varphi_2), \dots, x_{n-1}(t-\varphi_{n-1}), x_n(t-\varphi_n)\right]^T \tag{5}$$

with initial conditions