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Research article

Modified reduced order observer based linear active disturbance rejection control for TITO systems

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ABSTRACT

This paper proposes an observer based control approach for two input and two output (TITO) plant affected by the lumped disturbance which includes the undesirable effect of cross couplings, parametric uncertainties, and external disturbances. A modified reduced order extended state observer (ESO) based active disturbance rejection control (ADRC) is designed to estimate the lumped disturbance actively as an extended state and compensate its effect by adding it to the control. The decoupled mechanism has been used to determine the controller parameters, while the proposed control technique is applied to the TITO coupled plant without using decoupler to show its efficacy. Simulation results show that the proposed design is efficiently able to nullify the interactions within the loops in the multivariable process with better transient performance as compared to the existing proportional-integral-derivative (PID) control methods. An experimental application of two tanks multivariable level control system is investigated to present the validity of proposed scheme.

1. Introduction

Many industrial processes are complex and intrinsically multivariable in nature, and the problems like interactions, couplings, unmodeled dynamics, parameter uncertainties are always encountered in multi-input multi-output (MIMO) processes. It demands multivariable control design with better transient performances in presence of undesirable effects. Two-input two-output (TITO) system is a general class of multivariable process. The presence of the loop interactions, dynamic coupling, etc. are responsible for poor control performance and the design of multi-loop control is more challenging than single loop control. The effects of decoupling and stability of decoupled systems for TITO processes are discussed in [1]. Many researchers like Vinante and Luyben [2], Wood and Berry [3] and Ogunnaike and Ray [4], have examined a large number of particular multi-loop control systems which comprise of single input single output (SISO) controllers acting on a multi-loop design. The extension of SISO controllers in multiple single loops forms a multivariable control design. Due to the superiority, structural simplicity, ease of implementation and easy to tune, proportional-integral-derivative (PID) controllers are widely used in the majority of control systems as a standard feedback controller. Also, PID can provide better cost/benefit ratio as well as satisfactory performances. With these benefits, it was widely used in industry during the period of 1920–1990s [5], and around 90% of the practical industrial processes are stabilized and controlled using SISO-PID-Controllers [6]. In multivariable case, decentralized PID controller is extensively used due to its simple structure, and tuning simplification [7–10]. The PID controllers have some limitations such as error computation, complications arise due to integral control, and noise degradation in the derivative control, etc. [11]. Therefore, there is a requirement of further developments in PID framework. The technique active disturbance rejection control (ADRC), was investigated to overcome the identified problems associated with PID [11].

Most of the existing passive anti-disturbance control techniques are constructed from the mathematical description of plant dynamics. Many physical plants in the real world are nonlinear and time-varying as well as highly uncertain, hence, mathematical information of physical plants are not obtained accurately in an industrial context. Thus, an active anti-disturbance control is introduced with linear error feedback controller structure with compensation components which can automatically detect system model and the role of external disturbance in real time [11]. The introduced controller architecture accounts for total uncertainties including the internal uncertainties and external disturbances. Such control technique called as an ADRC [11], offers a robust controller building block where the system model is extended as new state variable with unknown dynamics and disturbances.

The concept of ADRC and its applications were introduced by Prof. Jingqing Han first time in Chinese literature in 1998 [12].

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ADRC strategy is analyzed in the time domain as well as frequency domain for different types of systems have been reported in the literature. The transfer function model of ADRC has been determined, and frequency domain analysis is carried out to evaluate the performance and stability characteristics of systems [13]. The frequency domain analysis of non-linear ADRC using describing function method is employed for LTI plant [14]. Li et al. [15], uses the root locus analysis, describing function and extended circle criterion to approach frequency domain stability analysis of servo system. In [16], it is shown that time domain analysis of linear ADRC can be used for a broad class of physical processes, when the model is known and unknown, which is estimated using ESO. A time domain approach of ADRC for non-linear, time-varying plant by singular perturbation concept has been explained in [17]. An ADRC has particular component as ESO, which plays a vital role in estimating external disturbance as well as internal dynamics, and it is also validated that such uncertainty can be reduced using ADRC [18]. A review of the methods which improves the overall efficiency of extended state observers has been given in [19]. Many ADRC applications have been noted in the literature. Some practical industry-wide applications of ADRC has been introduced in [20]. The independent model ADRC gives better performance than PID control for motion control design application [21]. ADRC has been efficiently implemented on motion control problem [22–25]. As ADRC is the technique that does not depend on the mathematical model of the plant, which makes it a better solution to industry application like MEMS Gyroscope [26–30]. Back-stepping active disturbance rejection control with reduced order ESO is designed for integrated missile guidance in [31]. The concept of ADRC has been implemented successfully in many applications, e.g. web tension and velocity regulation [32,33], twin rotor multi-input multi-output system [34], chemical-process control [35,36], boiler-turbine unit [37], Alstom gasifier [38].

The key component of ADRC, extended state observer (ESO) which can track the extended state of a class of uncertain plant satisfactorily by choosing proper functions and related parameters of the observer [39]. ADRC has the strong quality as the error driven rather than model based control law. Also, it offers a ESO which estimates extended state as a lumped disturbance includes parametric uncertainties, external disturbances, and cross coupling effect in multivariable processes. These promising features of ESO makes ADRC, a better solution to multivariable systems. A transformation based nonlinear control approach for uncertain multivariable systems with time delay has been presented in [40]. The issue of rejecting the disturbance in industrial processes with transport delay was focused, and the addressed problem was overcome by designing ADRC combined with smith predictor strategy [41]. Also, a modified active disturbance rejection control design has been offered for time delay systems [42]. A state space based nonlinear control approach has presented in [40] for TITO system, which is demonstrated in simulation environment without a proper method for tuning of nonlinear feedback parameters as well as for observer gain. In this paper, a linear ADRC methodology is extended to solve the problem of tuning of controller parameters for TITO systems. The proposed control technique is based on decoupled systems obtained from initially coupled plant. The tuned control law is especially applied to originally coupled system directly, and yet it handles the interactions efficiently. In the proposed technique, the control gains are selected from the boundary region of the controller where boundary region is obtained by considering reduced order model of decoupled systems.

The closed loop stability in presence of time delay of the plant have been investigated. The D-partition boundaries for closed loop system are plotted and stability regions are identified to make proper selection of controller parameters. A gain-phase margin approach [43] is employed to find the stability boundaries as well as pre-specified gain-phase margin boundaries. The D-partition technique [44] is used to obtain the stable region for controller parameters and the Kharitonov theorem is utilized to determine the robust stability boundary. The performance of proposed method under parametric uncertainty as well as external disturbance and stochastic disturbance has been carried out in a simulation environment and is experimentally validated for two tanks multivariable level control setup.

The remainder of this paper is organized as follows. The problem and objective is stated in Section 2. Section 3 presents the linear ADRC and reduced order linear ADRC. D-partition and identification of stability region with gain-phase margin approach is introduced in Section 4. In Section 5, application of modified reduced order linear ADRC to TITO process is explained by considering a case study of Wood and Berry distillation column, followed by its simulation results in Section 6. Modeling of an experimental setup of two-input two-output plant is given in Section 7 succeeded by its experimental results in Section 8. Finally concluding remarks are summarized in Section 9.

2. Problem statement

Consider a two-input two-output system as shown in Fig. 1. The input-output relationships are given by

$$y_1(s) = G_{11}(s)u_1(s) + G_{12}(s)u_2(s) \tag{1}$$

$$y_2(s) = G_{21}(s)u_1(s) + G_{22}(s)u_2(s) \tag{2}$$

where, $G_{11}(s)$, $G_{12}(s)$, $G_{21}(s)$ and $G_{22}(s)$ are the four transfer functions relating to the two-outputs corresponding to the two-inputs. As stated in Eqs. (1)–(2), the change in control signals due to coupling phenomenon will affect the controlled outputs y_1 and y_2 respectively.

It is proposed to consider the two-input two-output system affected by the lumped disturbance which includes the effect of cross couplings within the loops, parametric uncertainties, and external disturbances. Thus, the objective is to design the control input u_1 and u_2 such that the plant outputs y_1 and y_2 will follow desired response in presence of lumped disturbance.

In order to explain the basic idea of ESO based ADRC, primarily first order plus time delay (FOPTD) system is considered. Furthermore the reduced order ESO based linear ADRC for FOPTD plant has discussed. The results are further extended to TITO plant in Section 5.

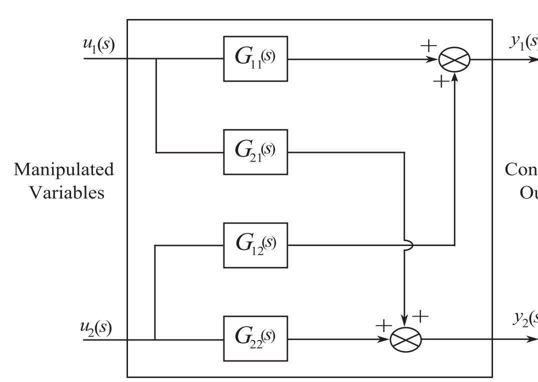

Fig. 1. Block diagram of process with two controlled outputs and two manipulated inputs.

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