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Robust tuning of a first order reduced Active Disturbance Rejection Controller

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ABSTRACT

In this paper, the robust tuning rules for a first order reduced ADRC (Active Disturbance Rejection Controller) are suggested for lag dominated processes. Based on the D-partition method and FOPDT (First Order plus Dead Time) process approximation, a software tool is designed that allows for tuning subject to phase and gain margins. Based on this software, six robust tuning rules were derived. For these rules, the results of simulation validation in the application to benchmark processes are presented and compared to the performance of PI-based control systems. Additional experimental validation shows the practical applicability of the suggested tuning rules.

1. Introduction

The Active Disturbance Rejection Control (ADRC) methodology has been established as a new paradigm in control theory (Gao, 2013). As an observer-based technique that practically requires no model at the derivation stage, it links the powerful tools of modern control theory with the simplicity and generality of a conventional PID controller. The basic concept of ADRC is based on the assumption that all external disturbances and internal (even strongly nonlinear) dynamics can be lumped together as a *total disturbance* and effectively estimated (and consequently rejected) by application of Extended State Observer (ESO) written in unified form. This approach allows for reducing the model of even a complex and nonlinear process into a simple cascade of integrators (Madoński & Herman, 2015; Zheng, Gao, & Gao, 2007). Consequently, the most time consuming stage of modeling is not required for ADRC synthesis. It is only required to determine (I) the relative order of the controlled process, which theoretically implicates the order of the ADRC controller and (II) the value of the so called *generalized amplification coefficient* (GAC) (Zhao & Huang, 2012).

Historically, the first English introduction to the ADRC technique was made by Gao, Huang, and Han (2001) as a novel nonlinear control algorithm with a nonlinear observer. Due to the relatively high number of tuning parameters, the tuning procedure for this approach was complex but even then, some tuning rules were proposed, based on e.g. bacterial foraging optimization and particle swarm optimization (Liu, Chu, Wang, & Zhang, 2013) or on FOPDT (First Order Plus Dead Time) step response approximation (Sun, Wu, & Zhu, 2009). Readers can also find successful applications of the nonlinear ADRC, e.g. Hou, Gao, Jiang, and Boulter (2001) but its practical linear simplification was proposed by Gao (2006), and this made ADRC more acceptable for control engineers lacking sufficient background in higher mathematics. However, this linear ADRC still requires the adjustment of relatively many tuning parameters, e.g. for the process of the second relative degree, three ESO gains and two ADRC controller parameters must be adjusted. This difficulty was solved in Gao (2003), where simplified tuning was suggested based on pole placement methodology. In simplification, ESO poles were suggested to be located based on observer bandwidth, while the controller poles were based on controller bandwidth. This method is very easy and effective, especially when the order of the ADRC controller is equal to the relative order of the process and when the value of GAC is accurate (Xue & Huang, 2015). Apart from its popularity within academia, ADRC has also become an interesting solution for industrial control systems (Gao & Rhinehart, 2004) and consequently, it has become a potential alternative not only to widely applied PID-based control systems but also to complex nonlinear model-based control techniques that so far have practically only been popular in academia. The ADRC technique provides improvement in control performance in comparison to the conventional PID controller, which has been shown by both simulation and experimental studies, e.g. Huang, Li, and Xue (2013), Liang, Li, and Li (2013), Madoński, Nowicki, and Herman (2014), Sun and Gao (2005) and Yuan, Du, and Yu (2015). But, there are two major difficulties that still limit its popularity among industrial control engineers.

One bottleneck is surely the choice of the appropriate ADRC order, which is an open question (Huang & Xue, 2014). Theoretically, this order should be equal to the relative degree of the controlled process (Zhao & Li, 2014) but this approach leads to a high order and complex

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ADRC design for processes of higher relative degree. At the same time, in industrial practice, the exact relative degree of a process can be difficult to determine and thus, it is advised to apply lower (or even first) order ADRC (Zhao & Huang, 2011). For further reduction of phase lag introduced by application of full order ESO, the reduced order ADRC (RADRC) approach is suggested (Huang & Xue, 2014; Zheng, Chedella, Xu, & Wu, 2011; Zheng, Daluom, Xu, & Zheng, 2012). For RADRC, the state observer is used to track only the total disturbance and the consecutive time derivatives of the controlled variable. Thus, its order is lower by one in comparison to the conventional ADRC approach with ESO of a full order where the measurable controlled variable is also tracked. At the same time, Zhao and Huang (2011) show that even the higher order open-loop stable processes can be stabilized by the close-loop system with first order ADRC. It is only required that the GAC value is relatively high. But, in such cases, the physical meaning of GAC is lost and it should be considered an additional tuning parameter (Chen, Li, Gao, & Wang, 2011; Zhao & Huang, 2011). In this study, this value is called the *scaling parameter*. Consequently, even for its simplest structure, ADRC still requires the adjustment of one additional parameter compared to the conventional and widely used PI controller.

The second and even more important obstacle to an increase in ADRC popularity in industrial control systems is the lack of relatively easy-to-use and reliable (robust) ADRC tuning rules that can be useful for practitioners. The accessibility of such tuning rules is definitely one of the most important advantages of the conventional PID controller and it allows for relatively easy implementation of PID-based control systems and their adaptation to industrial requirements. In the literature, readers can find some *rules of thumb* for ADRC tuning (Gao, 2013; Tian, Li, & Huang, 2012). However, more efficient tuning still requires trial and error methods combined with strong practical experience from the user. In particular, the key difficulty is the proper adjustment of the *scaling parameter*. Its value can be approximated based on a partial knowledge of the process (Chen et al., 2011) but if this knowledge is unavailable or if the simplified model of a process has a different structure from what was assumed during ADRC synthesis (e.g. for processes with a significant dead time), the value of the aforementioned *scaling parameter* must be chosen arbitrarily. In this respect, some directions and methods can be found in Madoński, Gao and Łakomy (2015). Another very promising and up-to-date approach is software-based ADRC tuning. This was suggested in Sun, Li, Hu, Lee, and Pan (2016) where the software tool for a first order ADRC controller with adjustable robustness (namely, maximum sensitivity function) is presented.

In industrial practice, it is expected that even for lag dominated processes, the presence of significant dead time should be successfully accommodated by a proper tuning method. In the literature for ADRC controllers, the concept of the Smith predictor is suggested for this purpose (Zhao & Gao, 2014; Zheng & Gao, 2014). However, even though this concept has been known for decades and suggested for different control techniques, its popularity in the practice is rather low. This results from the fact that its implementation requires additional effort. The difficulties multiply when the industrial control system is to be implemented in Programmable Logic Controllers (PLC) and this system consists of hundreds or even thousands of a single closed loops. Then, the computation complexity and data memory load become a very important issue and it has to be kept at the acceptable level. Thus, in this paper, it is advised to solve this problem by suggesting simple and easy-to-use robust tuning formulas for the first-order reduced ADRC controller in application to the lag dominated processes whose dynamics can be represented by FOPDT approximation. This approximation is still very common in industrial practice, because real processes usually exhibit significant (transportation) dead time. Then, FOPDT approximation can be determined based on experimental data obtained by a simple step response method (Marlin, 2000). The suggested tuning formulas were derived based on the D-partition method and on the advanced optimization-based software tool. The desired closed-loop robustness is defined by gain and phase margins while the tuning formulas are derived based on advanced numerical optimization of control performance measures, both for load disturbance rejection and for tracking properties. The suggested tuning rules were validated by simulation for different lag dominated FOPDT processes and for a clutch of benchmark processes of different dynamics. The final validation was conducted for a laboratory-scale industrially instrumented process. Consequently, the suggested tuning formulas are intuitive and easy to apply, even for process engineers who implement and maintain control systems and whose mathematical background is usually at B.S. level.

2. Synthesis of first order reduced ADRC for industrial processes

This paper focuses on control of lag dominated industrial processes that can be represented by the following general form of the input–output nonlinear dynamical model of the rth relative degree:

$$Y^{(r)}(t) = f\left(Y^{(r)}(t), \ldots, Y(t), \underline{d}(t), u\left(t - \tau_0\right)\right), \tag{1}$$

where Y denotes the measurable controlled output, u is the manipulating variable and τ_0 denotes the process dead time that directly results from mass or heat transportation phenomenon. Vector $\underline{d}$ consists of external process disturbances and the function $f(.)$ represents process nonlinearities. At the same time, the elements of vector $\underline{d}$ can be not measurable or even unknown. Thus, from a practical viewpoint, it is very common that there is a large structural and parametric uncertainty in the model (1). Consequently, its form cannot be applied as a basis for deriving any model-based controller without compensation for potential modeling uncertainties.

In industrial practice, it is advised to approximate even complex higher order process dynamics with the FOPDT (First Order Plus Dead Time) model (Marlin, 2000). Then, this FOPDT approximation can be successfully applied for synthesis of the first-order ADRC that has a simple form and can be tuned effectively. Following this path, it is assumed that the process under consideration (1) can be modeled by the following simplified FOPDT approximation:

$$Y^{(1)}(t) = \underbrace{\overbrace{-\frac{1}{T}Y(t) + \frac{k}{T}u\left(t-\tau_0\right)}^{FOPDT\ approximation} - b_0 u(t)}_{total\ disturbance\ F(t)} + b_0 u(t), \tag{2}$$

where k, T and T_0 represent approximating FOPDT process parameters and respectively denote substitute: process gain, its dominant lag and dead-time. At the same time, Eq. (2) can be further simplified by introducing so-called *total disturbance* denoted by F. Then, the model is completed by a simplified description of the manipulating forward path with an adjustable scaling parameter $b_0 > 0$. Its value can be chosen based on FOPDT approximation at the operating point or adjusted arbitrarily by a user.

The conventional ADRC paradigm suggests deriving an extended state observer (ESO) for tracking both the controlled output Y and the unknown *total disturbance* F, based only on the on-line measurements of Y and u. But, the reduced order observer design is also suggested, which leads to a reduced-order ADRC (RADRC) approach. This approach not only simplifies controller design and its computational complexity but also decreases phase lag introduced by ESO. For the considered FOPDT approximation, the unknown value of F is reconstructed from its estimate $\hat{F}$, based on the reduced first-order observer:

$$\hat{F}^{(1)} = \omega_0 \cdot \left(Y^{(1)} - \hat{F} - b_0 \cdot u\right), \tag{3}$$

where $\omega_o > 0$ is the observed bandwidth that stands as the tuning parameter and determines the observer convergence rate. The form of Eq. (3) is not convenient because it requires numerical differentiation of (usually noisy) measurement of Y. Thus, the auxiliary variable $z = \hat{F} - \omega_0 \cdot Y$ is defined, and Eq. (3) is rewritten as:

$$z^{(1)} = -\omega_0 \cdot \left(z + \omega_0 \cdot Y + b_0 \cdot u\right), \tag{4}$$