ARTICLE IN PRESS

ISA Transactions ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Combined feedforward and model-assisted active disturbance rejection control for non-minimum phase system

Li Sun [a], Donghai Li [a], Zhiqiang Gao [b], Zhao Yang [c,*], Shen Zhao [d]

[a] State Key Lab of Power Systems, Department of Thermal Engineering, Tsinghua University, Beijing 100084, China
[b] Center for Advanced Control Technologies, Cleveland State University, Cleveland, OH 44115, United States
[c] Department of Mathematics, Baylor University, Waco, TX 76798, USA
[d] National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA

ARTICLE INFO

Article history:
Received 8 October 2015
Received in revised form
17 March 2016
Accepted 19 April 2016

Keywords:
Active disturbance rejection control (ADRC)
Extended state observer (ESO)
Non-minimum phase (NMP) system
Inverse response

ABSTRACT

Control of the non-minimum phase (NMP) system is challenging, especially in the presence of modelling uncertainties and external disturbances. To this end, this paper presents a combined feedforward and model-assisted Active Disturbance Rejection Control (MADRC) strategy. Based on the nominal model, the feedforward controller is used to produce a tracking performance that has minimum settling time subject to a prescribed undershoot constraint. On the other hand, the unknown disturbances and uncertain dynamics beyond the nominal model are compensated by MADRC. Since the conventional Extended State Observer (ESO) is not suitable for the NMP system, a model-assisted ESO (MESO) is proposed based on the nominal observable canonical form. The convergence of MESO is proved in time domain. The stability, steady-state characteristics and robustness of the closed-loop system are analyzed in frequency domain. The proposed strategy has only one tuning parameter, i.e., the bandwidth of MESO, which can be readily determined with a prescribed robustness level. Some comparative examples are given to show the efficacy of the proposed method. This paper depicts a promising prospect of the model-assisted ADRC in dealing with complex systems.

1. Introduction

Non-minimum phase (NMP) systems with inverse response are widely encountered in industry, such as the fluidized bed combustor (FBC) [1], continuous stirred tank reactor [2] and water turbine [3]. The positive zero of the NMP system puts severe limitations on the bandwidth [4,5] of the feedback control system, making the control design quite challenging in terms of the following aspects:

1. For reference tracking, the conventional feedback design cannot produce an optimal tracking performance with a prescribed constraint on the magnitude of the inverse response [6].
2. For disturbance rejection, special care should be taken for the disturbance estimation, or it would lead to instability [7].

Recently, a feedforward control law was proposed in [8] to address the first problem, where a minimum settling time is achieved subject to a specified undershoot constraint. However, as is well known, the feedforward control is incapable of dealing with the modeling uncertainties.

In the past decades, Active disturbance rejection control (ADRC) emerges as an efficient control strategy in dealing with unknown disturbances and uncertainties. Many successful applications for minimum-phase systems can be found in [9–16], where a cascade-integral form is used as the canonical form for Extended State Observer (ESO) design. Such canonical form, however, could be problematic for the systems with mismatched uncertainties and disturbances, the time-delay systems and the NMP systems since they cannot be compensated as cascaded integrators, as reported in the latest survey [17–19]. In recent years, some elaborate methods been designed in [20,21] to reduce the effects of mismatched uncertainties. Also, the research in [22–24] were carried out to modify ADRC to be suitable for the systems with time delay. However, the ADRC design for the NMP system is still challenging with only limited preliminary results. The transfer function analysis in [25] suggests that the regular ADRC designed based on the relative order of the NMP system tends to be unstable. A modified ESO was constructed in [26] to decouple the negative effects of the right-half plane (RHP) zero.

* Corresponding author. Tel.: +1 2542979851.
E-mail addresses: sunli12@mails.tsinghua.edu.cn (L. Sun), lidongh@tsinghua.edu.cn (D. Li), z.gao@ieee.org (Z. Gao), Zhao_Yang@baylor.edu (Z. Yang), teddy__zhao@hotmail.com (S. Zhao).

http://dx.doi.org/10.1016/j.isatra.2016.04.020
0019-0578/

It should be pointed out that ADRC is more or less model-free for most minimum phase systems. But this property no longer holds for the NMP system with positive zeros. Because if the NMP plant is reduced to the form of the cascaded integrators using the regular ESO, it means that the RHP zeros will have to be cancelled by the identical unstable poles. That is, the canonical form of the chained integrators can only be achieved by the pole-zero cancellation in the RHP, which is not allowed under any circumstances. In this sense, we want to address that the model information is a premise for the ADRC design on NMP systems.

In this paper, the model information pertaining to the NMP dynamics is taken into consideration in the ESO design. If the designer knows nothing about the non-minimum phase characteristics, especially the position of the positive zero, the stability of the closed-loop system cannot be guaranteed in the ADRC design. This is similar to the ADRC design for the time delay systems [22–24].

This paper differs from the preliminary conference papers [25,26] in terms of the following aspects:

- The conventional cascade-integral form is replaced by the observable canonical form of the nominal model.
- The conventional feedback controller is replaced by a feedforward controller to produce a satisfactory tracking performance.
- The convergence of the method is analyzed.
- The proposed method is easy to implement because the servo and regulation design are decoupled.

The remainder of the paper is organized as follows: the problem is formulated in Section 2. Section 3 presents the combined structure of the feedforward control and ADRC, namely, modified ADRC (MADRC). Analysis on convergence, stability, steady-state characteristics and robustness are given in Section 4. Comparative simulation is carried out in Section 5 and the conclusions are reached in Section 6.

2. Problem formulation and the design strategy

2.1. Tracking control for NMP systems

Control of the NMP system is challenging due to the additional phase lag in frequency domain and the reverse response in time domain. For set-point tracking, it is difficult for the conventional feedback controller to achieve a fast tracking performance with a prescribed undershoot constraint.

To this end, Zhao [8] proposed an open-loop feedforward compensation law to achieve a minimum settling time subject to undershoot constraint. The design procedure is very simple, which is listed as the following two steps:

Firstly, compensate a general NMP system $G(s)$ as the following form,

$$\frac{Y(s)}{U_1(s)} = P(s) = C(s)G(s) = \frac{1-s/z}{(1+s/p)^{n+1}} \tag{1}$$

where $C(s)$ is the series compensator, z the RHP zero and $-p$ is the pole that is far from the origin. Usually, it is reasonable to set p within the range of (5, 10).

Secondly, the control law to generate u_1 is designed as follows:

$$u_1(t) = \begin{cases} (e^{z(t-t_0)}-1)ra_{us}, & t\in[t_0,t_1) \\ r, & t\in[t_1,\infty) \end{cases} \tag{2}$$

where, t_0 is the time when the set-point is changed, a_{us} is the allowable undershoot and

$$t_1 = t_0 + \frac{\ln(1/a_{us}+1)}{z} \tag{3}$$

Note that the primary shortcoming of this feedforward control law is that it is sensitive the modelling uncertainties in $G(s)$ and cannot accommodate the external unknown disturbances. This problem is expected to be handled by ADRC in this paper, to which we turn next.

2.2. Fundamentals of ADRC

Consider an n-th order dynamic system with single-input u and single-output y,

$$y^{(n)}(t) = f\left(y^{(n-1)}(t), \cdots y(t), w(t)\right) + bu(t) \tag{4}$$

where w is the external disturbance, b is a gain parameter, and f denotes an unknown combination of the system states and disturbances. By extending the 'total disturbance' f as an additional state, the system (4) can be represented as an augmented state space model.

$$\begin{aligned} \dot{x} &= Ax + Bu + Eh \\ y &= c^T x \end{aligned} \tag{5}$$

where $x = [x_1,\ x_2,\ \cdots\ x_n,\ x_{n+1}]^T = [y,\ \dot{y},\ \cdots\ y^{(n)},\ f]^T$, $h = \dot{f}$, $c^T = \begin{bmatrix} 1 & 0 & \dots & 0 \end{bmatrix}_{(n+1)\times(n+1)}$ and

$$A = \begin{bmatrix} 0 & 1 & & \\ \vdots & & \ddots & \\ 0 & & & 1 \\ 0 & \dots & \dots & 0 \end{bmatrix}_{(n+1)\times(n+1)}, B = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ b \\ 0 \end{bmatrix}_{(n+1)\times 1}, E = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 1 \end{bmatrix}_{(n+1)\times 1} \tag{6}$$

An extended state observer (ESO) is designed for system (5) accordingly as follows:

$$\begin{aligned} \dot{\hat{x}} &= A\hat{x} + Bu + L(y-\hat{y}) \\ \hat{y} &= c^T \hat{x} \end{aligned} \tag{7}$$

where, $\hat{x}$ aims at tracking x, and $L = [l_1\ \ l_2\ \ \dots\ \ l_{n+1}]^T$ is the observer gain. The convergence of ESO was proved in [27]. By compensating the estimated total disturbance $\hat{x}_{n+1}$ in real time,

$$u = \frac{u_0 - \hat{x}_{n+1}}{b} \tag{8}$$

the original system (4) can be reduced to

$$y^{(n)} = f + bu = f + u_0 - \hat{x}_{n+1} \approx u_0 \tag{9}$$

which is the enforced plant, i.e., cascaded integrators. Then, the outer controller for the enforced plant (9) can be determined straightforwardly as a state feedback law:

$$u_0 = k_1(r-\hat{x}_1) + k_2(\dot{r}-\hat{x}_2) + \dots + k_n(r^{(n)}-\hat{x}_n) \tag{10}$$

where r is the reference. The observer gain L and feedback gain k_i can be easily tuned based on the bandwidth-parameterization method in [28].

2.3. Disturbance rejection for NMP systems

Note that the system (4) does not contain zeros, and thus cannot describe the following transfer functions,

$$G(s) = \frac{y(s)}{u(s)} = \frac{b_m s^m + b_{m-1}s^{m-1} + \dots + b_1 s + b_0}{s^n + a_{n-1}s^{n-1} + \dots + a_2 s^2 + a_1 s + a_0}, \quad (m \le n) \tag{11}$$

Please cite this article as: Sun L, et al. Combined feedforward and model-assisted active disturbance rejection control for non-minimum phase system. ISA Transactions (2016), http://dx.doi.org/10.1016/j.isatra.2016.04.020