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Disturbance rejection control for non-minimum phase systems with optimal disturbance observer

Lu Wang, Jianbo Su *

Department of Automation; Key Laboratory of System Control and Information Processing, Ministry of Education, Shanghai Jiao Tong University, Shanghai 200240, PR China

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ABSTRACT

This paper investigates the disturbance rejection control for stable non-minimum phase (NMP) systems with time delay. A robust disturbance observer (DOB) based control structure is proposed. Specifically, the robust DOB is employed to compensate the uncertain plant into a nominal one, based on which a prefilter is adopted to acquire desired performance. Then, a novel DOB configuration strategy for stable NMP systems is proposed. This strategy synthesizes the internal and robust stability, relative order and mixed sensitivity design requirements together to establish the optimization function. The optimal solution is obtained by standard H_∞ theory under the condition of guarantying the presented requirements. We also investigate how the DOB can compensate the uncertain plant into a nominal one. The specifical design procedure is presented for an uncertain plant with both unstable zeros and time delay.

1. Introduction

In most practical industrial processes, the inevitable system uncertainties and external disturbances will have great influence on the performance of control system [1]. The efficient disturbance rejection method is the compensation by the estimation of model mismatch and external disturbances [2–5]. The disturbance observer (DOB) based control method was originally proposed by Ohnishi in 1987 [6], whose effectiveness in disturbance rejections has been shown in many applications, such as humanoid joint control [7], robot manipulators control [8], aircraft control [9], optical disk control [10], motor control [11], vibration control [12,13], ball mill grinding circuits control [14,15], etc.

DOB consists of a nominal model and a low-pass filter named Q filter. The design of Q filter is the key point of DOB configuration, which attracts many researchers' attentions. Typical filter forms, such as the binomial coefficient and Butterworth filter [16,17] are widely used. At this point, the performance mainly depends on the cut-off frequency. However, selection of parameters mainly depends on experiences, while there is no specific criterion for evaluation. The performance of system is largely limited by the fixed form of Q filter. Moreover, the robust stability can only be analyzed after the Q filter is determined. This means that we should repeat the design procedure until the robust stability requirement is guaranteed. There have been abundant results in using the H_∞ theory for Q filter design [18–20]. Linear Matrix Inequality or Algebraic Riccati Equation is applied in [18,19] to optimize the Q filter with static gain. The standard H_∞ theory is employed in [20] to optimize the Q filter.

However, these researches neglect the internal stability of the system, and these methods cannot be used directly in non-minimum phase (NMP) systems. Since the inverse of nominal plant is required in DOB configuration, the internal stability problem occurs if the nominal plant has the right-half of the s-plane (RHP) zeros. Meanwhile, the inverse of nominal model is non-causal according to the time delay. The configuration of DOB based control system for NMP system has been widely concerned in recent years. The authors present a DOB based model predictive control (MPC) method for a NMP process with time delay [14,15]. However, RHP zeros of the plant are not considered. In [21,22], a new filter in parallel with the Q filter is designed, and hence the parallel connection with the plant becomes of minimum phase. Then the conventional DOB configuration procedure is employed for the new system. A non-causal, minimum phase transfer function is proposed in [23] to remove the internal stability problem caused by RHP zeros. Nevertheless, the time delay is not considered in these methods. The improved DOB-MPC scheme is proposed in [24] for stable NMP systems, in which both RHP zeros and time delay are taken into account. An allpass portion is introduced in the Q filter to eliminate the influence caused by the

* Corresponding author.
E-mail address: jbsu@sjtu.edu.cn (J. Su).

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NMP property of the plant. However, both internal and robust stability of the system are not considered and the performance of the DOB is not analyzed specifically. In summary, although there are several researches in DOB configuration for NMP system, there is no systematic design of DOB for such system with both RHP zeros and time delay.

In this paper, we focus on the DOB based controller design for NMP systems. A novel DOB configuration strategy is proposed systematically. We first consider the robust internal stability, relative order, mixed sensitivity design requirements together to establish an optimization function. Then, the optimization problem is transformed into a standard H_∞ one, based on which the solution of Q filter is optimized by the existing standard H_∞ theory. We also investigate how the DOB can compensate the real plant into the nominal one. At last, a design example is presented specifically on an uncertain plant with both RHP zeros and time delay. In summary, the proposed strategy can be successfully employed in the DOB configuration for stable NMP systems, and the main contributions of this paper are presented as follows:

(1) A systematic design strategy of DOB is proposed for stable NMP systems by taken both RHP zeros and time delay into account.
(2) The optimization function is established by taken robust internal stability, relative order, mixed sensitivity design requirements into account together.
(3) The solution of Q filter is optimized by introducing the allpass portion into virtually controlled objective of H_∞ problem, based on which the unstable poles of inverse of nominal plant can be eliminated for robust internal stability constraints.
(4) Discussions on how the DOB can compensate the real plant into the nominal one are presented, which are verified in the simulations.

The rest of this paper is organized as follows. In Section 2, the control structure of the system is analyzed and the NMP problem is stated. In Section 3, we give the constraints of controller and DOB using internal stability principle, then the DOB is designed to acquire desired requirements. The performance of the proposed DOB is also under exploration. In Section 4, we consider a stable NMP plant with RHP zeros and time delay to implement the design procedure specifically. In Section 5, simulation on a rotary mechanical system is carried out to show the effectiveness of the proposed method, followed by Conclusions in Section 6.

2. Problem formulation

The traditional control system based on DOB is expressed in Fig. 1, where $P(s)$ is the plant model, $P_n(s)$ is the nominal model, $C(s)$ and $Q(s)$ are the controller and Q filter to be designed. $R(s), Y(s), D(s)$ and $N(s)$ denote the Laplace transformation of reference input r, output y, external disturbances d and measurement noise n, respectively. τ is the dead-time of the plant while τ_n is its nominal value. DOB considers the mismatch between real plant and nominal one as equivalent disturbance acting on its nominal model. It can estimate the equivalent disturbances

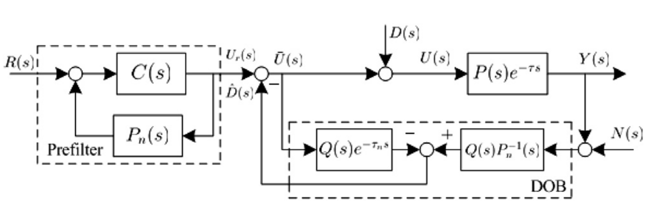

Fig. 1. The DOB based controller for the NMP system.

combined with the external disturbances, and feed back the estimated disturbances for cancellation. Then the controller is applied as a prefilter to stabilize the nominal system compensated by DOB for desired performance. This control system has two degrees-of-freedom (2DOF). Hence, the DOB can be optimized for disturbance rejection performance and then the prefilter can be chosen independently for setpoint tracking performance. In this control system, the design and optimization of controller and DOB can be implemented separately.

The control objective is to design the DOB to attenuate the compound disturbance caused by model mismatch and external disturbances. Then, a prefilter is designed to stabilize the nominal model to acquire desired performance. Since DOB can estimate the compound disturbances, the controller $C(s)$ can be designed based on the nominal plant $P_n(s)$. Here, H_2 theory is applied to design the controller $C(s)$ and the prefilter can be obtain as:

$$\frac{C(s)}{1+C(s)P_n(s)}. \tag{1}$$

For the NMP systems, the inverse of the RHP zeros and time delay is physically unrealizable for its non-causal property. The internal stability is a basic requirement for a practical closed-loop system, but unfortunately, in the research work of DOB design, the internal stability analysis for this kind of system has been only discussed in [25]. Moreover, most DOB design methods only validate the robust stability after the parameters of the DOB are determined. It is a complicated work for us to adjust the parameters repeatedly to guarantee the robust stability. Thus, in this paper, we mainly focus on the systematic design strategy of DOB for stable NMP systems. The system model $P(s)$ is described with multiplicative uncertainty as:

$$P(s)=P_n(s)(1+\Delta(s)), \tag{2}$$

where $P(s)$ and $P_n(s)$ are all stable plants with NMP property. The nominal model $P_n(s)$ is expressed as:

$$P_n(s)=\frac{N(s)}{D(s)}\prod_i(-s+\xi_i), \tag{3}$$

where $Re(\xi_i)>0$, $N(s)$ and $D(s)$ have no root with positive real part.

3. Robust DOB design

The transfer function of the DOB structure can be written as:

$$Y(s)=M^{-1}(s)[P(s)e^{-\tau s}(1-Q(s)e^{-\tau_n s})D(s)+P(s)e^{-\tau s}U_r(s) \\ -P_n^{-1}(s)P(s)Q(s)e^{-\tau s}N(s)]. \tag{4}$$

where $M(s)=1+P_n^{-1}(s)P(s)Q(s)e^{-\tau s}-Q(s)e^{-\tau_n s}$.

From Eq. (4), we notice that the suppression performance against external disturbances d mainly depends on the factor $(1-Q(s)e^{-\tau_n s})$. However, it is very hard for us to optimize $Q(s)$ directly with time delay. By introduce the notation $Q'(s)\triangleq Q(s)e^{-\tau_n s}$, we can consider $Q'(s)$ directly. Then, $Q(s)$ can be obtained by replace the time delay $e^{-\tau_n s}$ with a Padè approximation. Eq. (4) can be rewritten as:

$$Y(s)=M^{-1}(s)[P(s)e^{-\tau s}(1-Q'(s))D(s)+P(s)e^{-\tau s}U_r(s) \\ -P_n^{-1}(s)P(s)Q'(s)N(s)]. \tag{5}$$

Assume that nominal model of the plant matches the real plant very well (i.e., $P(s)=P_n(s)$, $\tau=\tau_n$), then Eq. (5) can be simplified as:

$$Y(s)=P_n(s)e^{-\tau_n s}(1-Q'(s))D(s)+P_n(s)e^{-\tau_n s}U_r(s)-Q'(s)N(s). \tag{6}$$

From Eq. (6), we can see that $Q'(s)$ should be reduced as far as possible to attenuate the influence caused by measurement, whereas $1-Q'(s)$ should also be small to reject the external disturbances. These two conditions are conflicting. In practical