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Disturbance rejection performance analyses of closed loop control systems by reference to disturbance ratio

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ABSTRACT

This study investigates disturbance rejection capacity of closed loop control systems by means of reference to disturbance ratio (RDR). The RDR analysis calculates the ratio of reference signal energy to disturbance signal energy at the system output and provides a quantitative evaluation of disturbance rejection performance of control systems on the bases of communication channel limitations. Essentially, RDR provides a straightforward analytical method for the comparison and improvement of implicit disturbance rejection capacity of closed loop control systems. Theoretical analyses demonstrate us that RDR of the negative feedback closed loop control systems are determined by energy spectral density of controller transfer function. In this manner, authors derived design criteria for specifications of disturbance rejection performances of PID and fractional order PID (FOPID) controller structures. RDR spectra are calculated for investigation of frequency dependence of disturbance rejection capacity and spectral RDR analyses are carried out for PID and FOPID controllers. For the validation of theoretical results, simulation examples are presented.

1. Introduction

In real applications, control systems are exposed to environmental disturbances, mainly, in intermittent character and therefore these unpredictable disturbances may severely deteriorate the control performance. Robust control performance is possible for control systems in real world applications, when they exhibit adequate degree of disturbance rejection. Disturbance rejection control (DRC) aims a controller design reducing the negative effects of disturbances on the control performance, and it became one of the major concerns in the design of feedback control systems [1]. DRC design strategies provide a step towards disturbance tolerant control systems.

Several works were presented to deal with undesired influence of disturbance signals on the system output in the literature. These works can be taken into account in two folds: The one is explicit approaches that are employing additional functions and blocks designed for disturbance rejection proposes. The second is implicit approaches that are based on utilization of structural disturbance rejection capacity of control systems. Explicit methods contain additional functional blocks such as filters [2–4], disturbance and state observers [1,5], disturbance estimator [6], and a class of robust adaptive state feedback controllers [7]. Since additional function and blocks developed for disturbance rejection may complicate structure of control systems, explicit methods can lead to increased computational complexity in controller design and operations.

Implicit approaches rely on inherent disturbance rejection capacity of the conventional control structures without need for any additional blocks. Implicit approaches were addressed in many studies in the literature. Szita et al. suggested a frequency domain design methodology to obtain acceptable disturbance rejection according to a pre-specified reference model for time delay systems [9]. Koussiouris et al. presented frequency-domain conditions for disturbance rejection and decoupling with stability or pole placement [10]. In many works, disturbance rejection controller design problem were taken into account as the minimization of sensitivity function amplitude [11–13]. Besides, the disturbance rejection control based on high gain control was proposed the suppression of unknown disturbances, which are not usually accessible for measurement [1,8]. High-gain control was addressed in many works [14–17]. High-gain feedback design problems were solved for almost disturbance decoupling to find out a sequence of dynamic compensators for linear systems [14,16,17]. It was reported that one of the major problems with disturbance decoupling is that it could be achieved approximately with an arbitrary degree of accuracy [14]. Although high-gain control can reduce effects of unknown disturbance signal on system output, they may also encounter drawbacks of control

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saturation and high peaks in practice and therefore, they need precisely tuning and well-constrained designs for the real world applications. Yu et al. present the performance assessment of PI control loops for rejecting the input load disturbances by using a DS-d IAE-based performance index and a survey on stochastic and deterministic disturbance performance indices [18].

There is a need for the deterministic method for assessment of actual disturbance rejection capacity of closed loop control systems, which considers the tradeoff between reference and disturbance transmission toward the system output. The current study aims to derive straightforward analytical expressions showing spectral dependence of disturbance rejection capacity of closed loop control systems.

This paper is devoted in investigation of implicit disturbance rejection capacity of closed loop control systems on the bases of communication channel limitation. We analyzed reference to disturbance ratio (RDR) of closed loop control systems in a similar manner the signal to noise ratio (SNR) defined for communication channels. RDR measure is used to calculate quantitative assessment of reference input dominancy on disturbance at the system output. A control system shows a satisfactory disturbance rejection performance in the case of $RDR \gg 1$. If $RDR \le 1$, it can be stated that the control system does not exhibit any disturbance rejection skill. RDR spectra are obtained for spectral investigation of disturbance rejection control performance in this study. We assume unmeasured input disturbance, where unknown additive disturbance signals come into the control system from the plant input.

For the improvement of disturbance rejection performance, the proposed method utilizes limitations of control loop communication channel modeling for predominance of reference against the disturbances at the system output. Concepts of communication channel modeling in control loops were discussed in details [19]. In recent years, Rojas presented theoretical works imposing a communication channel in the control loop and addressed problem of feedback stabilization subject to a constraint on the channel signal-to-noise ratio (SNR) [20,21]. Rojas et al. demonstrated that communication channels impose limitations to feedback control [22]. Signal-to-noise ratio performance limitations were investigated for disturbance rejection and stability of the closed loop control system in [21].

For the analytical formulation of RDR method, we consider a negative feedback closed loop control system as the superposition of two low-pass communication channels. One is from reference input to the system output and the other is from disturbance input to the output. RDR spectrum is derived for closed loop control system and detailed analyses are carried out for PID controller family. Frequency dependence of disturbance rejection is investigated for classical PID and FOPID controller structures. Moreover, design criteria based on RDR performance specification are introduced for disturbance rejection PID and FOPID controller design problems. Matlab/Simulink closed loop control system simulations validate our theoretical findings. Disturbance rejection performances are compared for PID and FOPID controller designs.

Motivation of this study comes from the requirement for straightforward and practical formulation of disturbance rejection capacity of closed loop PID and FOPID control systems. This makes disturbance rejection performance of control systems measurable and comparable. Moreover elaborating impacts of design coefficients on disturbance rejection performance of closed loop PID controller family is very useful for controller practice. RDR specification in control design problems helps to improve robust performance of PID and FOPID controllers in real control application.

The paper is organized as follows: the following section was devoted for reference and disturbance channel modeling of a negative feedback control system and a general formula to express the ratio of reference signal to disturbance signal at the output is derived. In the further section, PID and FOPID controller design constraints for desired disturbance rejection are derived and illustrative examples are presented.

2. Methodology

2.1. Reference to disturbance ratio

Consider a closed loop control system as the superposition of two low-pass communication channels. The first channel is from the reference signal to output of control system and referred as to Reference Channel Control (RCC) and the other is from input of plant to the output of control system and referred as to Disturbance Channel Control (DCC). Fig. 1 shows a closed loop control system model with additive disturbance signal. Assuming a linear time invariant system, the system in Fig. 1 can be written as a superposition of two systems, namely RCC and DCC models, as illustrated in Fig. 2. Fig. 2(a) shows RCC system obtained in the case of a zero disturbance ($d=0$), and Fig. 2(b) shows DCC system in Fig. 1, when the reference signal is zero ($r=0$).

Lets denote the transfer function of RCC system given in Fig. 2 by $P_r(s)$. The $P_r(s)$ can be written as,

$$P_r(s)=\frac{Q(s)|_{d=0}}{r(s)}=\frac{C(s)G(s)}{1+C(s)G(s)} \tag{1}$$

Lets denote the transfer function of DCC system given in Fig. 2 by $P_d(s)$. The $P_d(s)$ can be written as,

$$P_d(s)=\frac{Q(s)|_{r=0}}{d(s)}=\frac{G(s)}{1+C(s)G(s)} \tag{2}$$

One can express output of the closed loop control system by superposing the RCC system output $Q_r(s)=Q(s)|_{d=0}$ and the DCC system output $Q_d(s)=Q(s)|_{r=0}$ as,

$$Q(s)=Q_r(s)+Q_d(s) \tag{3}$$

Ogata also expressed $Q(s)$ in an open form with respect to controller, plant and feedback transfer functions in order to figure out the necessary conditions for disturbance suppression at the control system output [8]. Ogata suggested the condition of $|C(s)G(s)| \gg 1$ to improve disturbance rejection performance of closed loop control systems with unity feedback. Because, in the case of high open loop gain ($|C(s)G(s)| \gg 1$), the transfer function from disturbance to system output $P_d(s)=Q(s)/d(s)$ goes to almost zero. However, suppression of reference signal by the control system should be also taken into account for a realistic evaluation of disturbance rejection performance in control point of view. We further deepen this perfective for the measure of disturbance

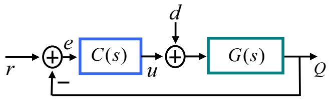

Fig. 1. A closed loop control system with additive input disturbance model.

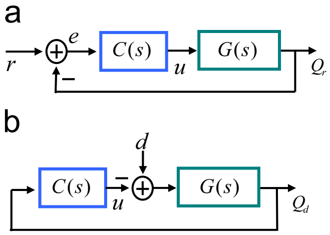

Fig. 2. (a) RCC system model obtained for zero disturbance ($d=0$); (b) DCC system model obtained for zero reference signal ($r=0$) of closed loop control system with additive disturbance model.