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Anti-windup disturbance feedback control: Practical design with robustness

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ABSTRACT

This paper presents a practical design method of robust disturbance feedback control (DFC) along with an application to industrial refrigeration systems. DFC is a controller configuration in which an existing controller is augmented with an additional loop. The design method for DFC is proposed in two steps; firstly, the robust DFC without saturation is designed by a linear matrix inequality (LMI) approach, and then LMI techniques are used again for designing an anti-windup compensator to accommodate actuator saturation. The proposed method is compared to a conventional design on a water chiller system, both in simulation and through practical experiments. The test results indicate that both robustness and performance can be improved in the presence of model uncertainties, and the proposed method can avoid wind-up phenomena when the control inputs are saturated.

1. Introduction

Disturbance feedback control (DFC) was originally developed by Fuji Electric in 1980 [1]. DFC has been applied in industrial systems for attenuating disturbances, such as motor drive systems [2]. In addition to a standard reference-following regulator, this control structure incorporates an additional *feedback* loop to compensate for disturbance and model uncertainties. The control structure can thus be categorized as a two-degree-of-freedom (2DOF) controller. Especially, a 2DOF control, composed of a stand PID control and DFC, can be chosen for practical design of industrial applications.

As for practical design with robustness, various tuning methods for PID control or low order controllers have been proposed, see e.g., [3–6]. In addition, methods for PID control design relying on optimization via linear matrix inequalities (LMIs) to satisfy certain stability and robustness requirements have been proposed [7]. Moreover, combinations of robust control and internal model control (IMC) have been proposed as new challenges in the literature [8].

Note that DFC is not the same as IMC [9] because DFC has two feedback signals, which means two degrees of freedom. Basic IMC has only one feedback signal, which will be zero when there is no modeling error. Also, DFC allows for a two-step design in which a classical controller is designed first, and then subsequently augmented by the extra feedback for better disturbance rejection.

In addition, the IMC structure and the classical feedback structure are equivalent representations [10]. Here, IMC and PI control as a classical feedback control can be equivalent, and therefore PI control with or without DFC will be compared in Section 3, instead of IMC. The challenges of adding new controllers and new subsystems to a plant are treated in related research on the plug & play control, see [11,12].

In a previous study, the authors presented a low order robust DFC for a water chiller system, to address the control issues of performance degradation due to non-linearities and load disturbances [13]. The robust DFC was found to improve the performance compared to conventional PI control. However, for a more practical design, an anti-windup scheme is necessary to handle the constraints of the control devices and actuators.

A tutorial on modern anti-windup design can be found in [14], in which two approaches, namely direct linear anti-windup and model recovery anti-windup, are presented. In addition, the authors state that most anti-windup designs can be formulated by LMIs. LMI-based anti-windup synthesis methods have been proposed for robust control of linear systems [15]. Another approach

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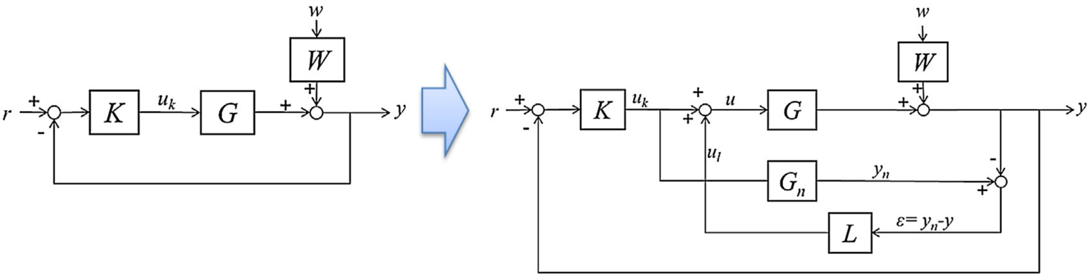

Fig. 1. Block diagrams of existing control systems (left), and the existing control with DFC (right).

in which a dead-zone is introduced for anti-windup control design, and a local control design technique is proposed, is presented in [16]. Anti-windup schemes for discrete time system using LMI based design were proposed by Rohman et al. [17] in order to address the issues of the algebraic loops of anti-windup controllers.

In general, anti-windup designs are considered for one-degree-of freedom (1DOF) controllers for closed loop systems. However, 2DOF controllers are used for many industrial applications because the systems need to guarantee both set point following and disturbance rejection responses.

Therefore, it could be useful for industrial applications to find a design method for anti-windup 2DOF controllers for discrete time systems. In addition, numerical analysis including experimental test is necessary to find out whether the previous studies can be applied for 2DOF systems as well.

For these reasons, this paper introduces an anti-windup compensator for 2DOF controllers, one for an existing controller and another for DFC, in a discrete time systems. The proposed design method is applied to superheat control and suction pressure control in a refrigeration system. Both simulations and experimental tests are examined to evaluate the robustness of DFC and the effectiveness of the anti-windup scheme, and clear performance improvements can be observed by the addition of DFC.

The rest of the paper first explains the DFC design method in Section 2, providing LMI formulations for DFC design with anti-windup compensation. After that, experimental results of refrigeration system control are demonstrated in Section 3. Finally, conclusions are given in Section 4.

2. DFC design

Fig. 1 shows block diagrams of an existing control system (left) and the same system augmented with DFC (right). The existing controller K is assumed to be a 1DOF controller, a PID controller for instance, and it may be designed by traditional methods; IMC, pole placement, or similar. W is a disturbance weighting transfer matrix.

On the right side, DFC is added to the existing control system to improve the robustness against disturbances. In addition, DFC can work to compensate for model uncertainties if there are modeling errors between the nominal model G_n and the actual plant G. Notice how the DFC control signal is added to the existing control signal after the u_k branch; this configuration makes DFC different from IMC [9].

Other variations of DFC can be described as shown in Fig. 2. In one variant, the existing controller is composed of a feedback and a feedforward part. In another variant, a weighting function W places more emphasis on certain disturbance frequency ranges. The method presented in the following applies to these variants as well with minor modifications.

This section presents a method to design the DFC to meet certain stability and robustness requirements. Firstly, the existing control systems are defined. Next, LMIs for the DFC synthesis are presented, and finally the controller is discretized and augmented with anti-windup.

2.1. Existing control systems

The plant model G in Fig. 1 is assumed given as a time domain representation in state space;

$$\dot{x} = Ax + Bu, \qquad (1)$$

$$y - d = Cx$$

where $A \in \mathbb{R}^{n\times n}$, $B \in \mathbb{R}^{n\times m}$, and $C \in \mathbb{R}^{m\times n}$ are real constant matrices. $x \in \mathbb{R}^{n}$ is the plant state, $u \in \mathbb{R}^{m}$ is the control input

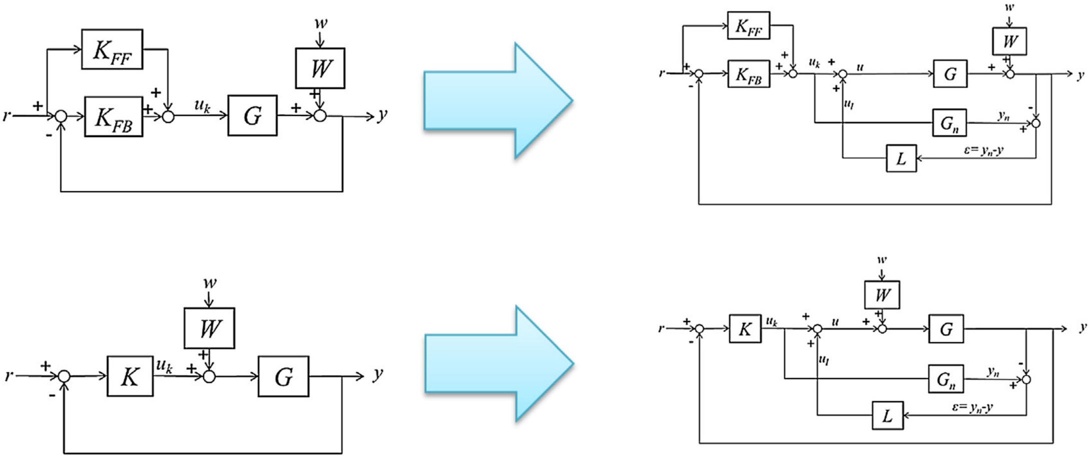

Fig. 2. Block diagrams of other variations about existing control systems (left), and the existing control with DFC (right).