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Experimental Evaluation of Reset Control for Improved Stage Performance

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Abstract: A reset integral controller is discussed that induces improved low-frequency disturbance rejection properties under double integrator control without giving the unwanted increase of overshoot otherwise resulting from adding an extra linear integrator. To guarantee closed-loop stability, a (conditional) reset condition is used that restricts the input-output behavior of the dynamic reset element to a $[0, \alpha]$-sector with α a positive (finite) gain. As a result, stability can be guaranteed on the basis of a circle criterion-like argument and checked through (measured) frequency response data. Both stability and performance of the control design will be discussed via measurement results obtained from a wafer stage system of an industrial wafer scanner.

Keywords: Circle criterion, Lyapunov stability, motion systems, reset control, wafer scanners.

1. INTRODUCTION

This paper discusses a reset integral controller design to cope with the conventional trade-off between a) improved low-frequency disturbance suppression through integral control and b) desired transient response, which in view of the mentioned integral control usually deteriorates. This trade-off generically arises in high-precision motion control applications like for example wafer scanners, which are used in the production of chips, and which require nanometer accuracies under aggressive motion profiles; for the control of wafer scanners see also (Butler, 2011).

Nonlinear control has been opted by many researchers (Seron & Goodwin, 1996) in an attempt to balance the above-mentioned trade-off in a more desirable manner. An interesting concept in this regard is reset control, see for example the Clegg integrator that later developed into first-order reset elements (FORE), see Clegg (1958); Horowitz & Rosenbaum (1975); Zaccarian et al. (2005). The Clegg integrator is a simple integrator that resets its state to zero upon zero input crossings. Its describing function possesses a 20 dB/decade amplitude decay with 38.15 degrees of phase lag instead of the 90 degrees phase lag corresponding to a linear integrator (Clegg, 1958).

With these advantages in mind, recently a variable-gain integrator with reset properties has been proposed by Heertjes et al. (2015). In this work, the variable-gain integrator with reset combines a variable-gain integral controller with a Clegg integrator. The measurement results obtained for this type of controller applied to a piezo-actuated lens system clearly demonstrated its benefits. Stability of the closed-loop reset system essentially boils down to satisfying two conditions: i) a flow condition in the intervals between resets, and ii) a jump condition at the resets, see also Aangenent et al. (2010); Baños et al. (2011); Beker et al. (2004); Zaccarian et al. (2005, 2011); Carrasco et al. (2010). For the base-nonlinear system, i.e., the variable-gain integrator without the reset, stability has been guaranteed by the application of the positive real lemma, thereby guaranteeing satisfactory the flow condition. For the closed-loop nonlinear system with reset, a quadratic Lyapunov function candidate is found that satisfies both the flow and the jump condition. This is done by pursuing an LMI-(linear matrix inequalities) based approach. In the high-precision industry, however, using LMI-based design conditions is considered as less desirable, because it requires a parametric model of the plant to be controlled, which is often difficult to obtain and which rarely meets the requirements imposed on model accuracy. Moreover, LMI stability analysis only renders limited physical or controller tuning insights compared to frequency-domain techniques, while this is crucial in support of the development of a generically applicable controller strategy.

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In this paper, inspired by Heertjes et al. (2015), a lag filter is used where the integrator is replaced by a Clegg integrator. The flow and jump sets are designed such that the input-output behavior of the reset element belongs to the sector $[0, \alpha]$ with $\alpha > 0$ a positive (finite) gain. Based on this insight, input-to-state stability of the closed-loop system with reset can be guaranteed by combining a circle criterion-like argument (Arcak et al., 2003) together with a detectability condition for the reset element; note that the latter includes an integrator, which is not memoryless, and thus requires extra attention beyond the conventional circle criterion argument. The above stability conditions can be assessed by evaluating (measured) frequency response data of the linear part of the closed-loop system in relation to the gain α. The main contributions of the paper are the application of this reset control to the wafer stage of an industrial wafer scanner and the demonstration of the frequency-domain design in practice.

The remainder of this paper is organized as follows. In Section 2, the reset control design is discussed in more detail. This includes a circle criterion-like stability argument that results in easy-to-check stability conditions. In Section 3, measurement results are discussed that are obtained by application of the reset controller to a wafer stage system. Section 4 summarizes the main conclusions.

2. RESET CONTROL DESIGN

Consider the reset control system in Fig. 1 where the nonlinear element, i.e., the reset integrator, captured in $\mathcal{R}$ is being isolated from the linear dynamics represented by $\mathcal{H}$. In the figure, r represents a reference to be tracked,

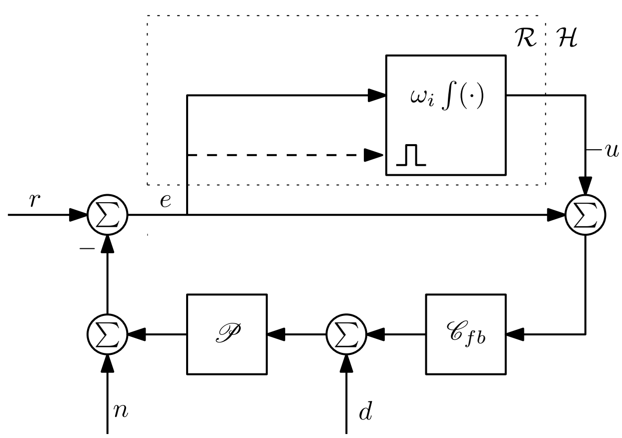

Fig. 1. Simplified schematics of a reset control system.

e is a closed-loop error signal, $\mathscr{C}_{fb}$ a nominal (linear) PID-based feedback controller, d a force disturbance, $\mathscr{P}$ the plant, n the output disturbance (e.g., sensor noise), and $-u$ the output of the reset integrator. For the ease of presentation, it should be mentioned that feedforward control, which does not affect the upcoming closed-loop stability analysis, has been omitted from the figure. However, all measurement results presented later on will include the effect of a mass/snap feedforward controller with delay compensation (having the motion control setting in mind).

To obtain stability conditions that allow for verification on the basis of frequency response data, the system in Fig. 1 is transformed to a Lur'e-type system, see Fig. 2. Note that the essential difference with a true Lur'e system lies in the fact that a *dynamical* nonlinear system $\mathcal{R}$ — $\mathcal{R}$ contains an integrator — is considered rather than a memoryless (and static) nonlinearity. In Zaccarian et al. (2005) it is

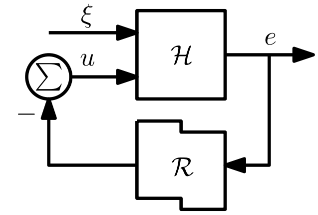

Fig. 2. Lur'e-type system representation.

remarked that a classical Clegg integrator (with input e and output $-u$) is characterized by the property that input and output can never have opposite signs. This particular property has been exploited in, e.g. Zaccarian et al. (2005), Nešić et al. (2008), and Aangenent et al. (2010), where the integrator resets whenever $eu \leq 0$. From the frequency-domain perspective such as pursued in this paper, this reset condition can be viewed as the input-output pair $(e, -u)$ corresponding to the sector $[0, \infty]$. Application of the (frequency-domain) circle criterion would then require $\mathcal{H}$ to be positive real, a feature that is rarely met in motion control applications. We therefore propose to choose the reset condition of the switching integral controller with reset such that the input-output pair $(e, -u)$ corresponds to the sector $[0, \alpha]$ with $\alpha \in \mathbb{R}_{>0}$ being constant. In the case of $\mathcal{R}$ being a static memoryless element, input-to-state stability of the closed-loop system as shown in Fig. 2 can be simply proved by evaluating the circle criterion. However, since $\mathcal{R}$ contains dynamical elements (in this case an integrator) additional arguments are needed to ensure internal stability of $\mathcal{R}$, and consequently ISS of the reset control system in Fig. 2 including this integrator state.

2.1 Closed-Loop Model Representation

Consider Fig. 2 where $\mathcal{H}$ represents a continuous-time LTI dynamical system that in state-space description reads

$$\mathcal{H} : \begin{cases} \dot{x}_h(t) &= Ax_h(t) + Bu(t) + B_\xi \xi(t) \\ e(t) &= Cx_h(t) + D_\xi \xi(t) \end{cases}, \qquad (1)$$

with $e(t), u(t) \in \mathbb{R}$, and $x_h(t) \in \mathbb{R}^{n_h}$ the state vector containing the (physical) states of plant $\mathscr{P}$ and feedback controller $\mathscr{C}_{fb}$ in Fig. 1 at time $t \in \mathbb{R}_{\geq 0}$. Moreover, $\xi(t) = [r(t)\ d(t)\ n(t)]^T \in \mathbb{R}^{3\times 1}$ denotes the augmented exogenous input vector, and (A, B, C) is assumed to correspond to a minimal realization. The transfer function between input $u(s)$ and output $e(s)$ of (1) is the complementary sensitivity function $\mathscr{S}_{ch}(s)$, which is given by

$$\begin{aligned} \mathscr{S}_{ch}(s) &:= C(sI - A)^{-1}B \\ &= \frac{\mathscr{P}(s)\mathscr{C}_{fb}(s)}{1 + \mathscr{P}(s)\mathscr{C}_{fb}(s)}. \end{aligned} \qquad (2)$$

Consider the nonlinear dynamical system $\mathcal{R}$ with input-output pair $(e, -u)$ which consists of the reset integrator and which is given by the following impulsive differential equation (IDE)

$$\mathcal{R} : \begin{cases} \dot{x}_i(t) &= \omega_i e(t), & \text{if } (e, -u) \in \mathcal{F}, \\ x_i(t^+) &= 0, & \text{if } (e, -u) \in \mathcal{J}, \\ -u(t) &= x_i(t). \end{cases} \qquad (3)$$