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VSS global performance improvement based on AW concepts☆

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Abstract

The influence of the reaching mode on the global performance of variable structure systems (VSS) undergoing sliding regimes is stressed. A comparative analysis between the behaviour during this reaching mode of operation and the problem of windup is realized. Based on the similarities between both control problems, some tools of the control theory of constrained linear systems are exploited to improve the reaching mode of VSS.

Keywords: Variable structure control; Sliding mode; Reaching mode; Windup; Constrained systems

1. Introduction

Variable structure systems (VSS) undergoing sliding motions (SM) have many attractive properties such as robustness to matched disturbances and reduced closed-loop dynamics (Utkin, Guldner, & Shi, 1999). Actually, a reaching phase (RM) precedes the establishment of the desired SM. Even though the latter has been more discussed in the literature, the former is not less important when the global performance is considered (Ryan & Corless, 1984). In fact, a long RM may seriously deteriorate the transient response. In the survey (Hung, Gao, & Hung, 1993), different approaches to the RM problem are summarized. Despite some interesting properties, these approaches focus on the surface coordinate dynamics instead of on the system dynamics, do not take into consideration the limits of the actuators, are not applicable when the control signal can only take some discrete values (such as in power electronics where the control signal represents the state of a switch) and are particular or intuition-based solutions (Hung et al., 1993; Mantz, De Battista, & Puleston, 2001).

The goal of this note is to draw a parallel between the RM and another control problem extensively discussed in recent years: reset-windup (RW). The significance of this correlation lies in the possibility of applying the strong theory of constrained systems to the RM problem. The basic idea is to shape the controller state, thus facilitating the establishment of the SM. In this context, a pair of compensation strategies to improve the RM in VSS is derived from classical anti-windup (AW) algorithms.

2. Problem formulation and main results

Fig. 1 sketches a VSS with the proposed RM compensation. P is the process to be controlled. Δ depicts the parametric uncertainties. Sw, that switches between the input signals u^+ and u^-, is driven by the output σ of the LTI controller $K(s) = C(sI - A)^{-1}B + D$. Let us assume for a moment that the RM compensation Λ of K is inactive, i.e. $\hat{K} = K$. The input to K is $v = \mathrm{col}(r, y, x_p)$, where r is the set-point, and x_p and y are the state and output of P (some nonlinear outputs $y = f(x_p)$ can be deliberately defined as inputs to K to address the case of nonlinear processes). The state of

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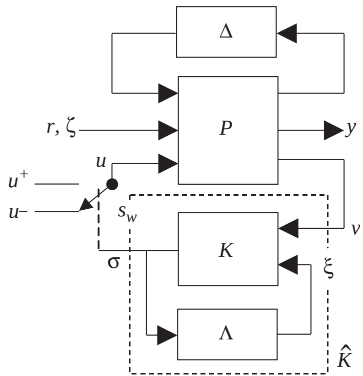

Fig. 1. VSS with proposed RM compensation.

$K(x_k)$ may include dynamic expansions to reject steady-state disturbances ζ (Bühler, 1986; Mantz, Puleston, & De Battista, 1999). On the contrary, to reduce chattering (Sira-Ramírez, 1993) the dynamic expansion must be inserted at the input u to P. Hereinafter, the following conventional notation is used (where only D has meaning in the case of static feedback):

$$K = \left[\begin{array}{c|c} A & B \\ \hline C & D \end{array}\right] = \left[\begin{array}{c|c|c|c} A & B_r & B_y & B_p \\ \hline C & D_r & D_y & D_p \end{array}\right]. \tag{1}$$

2.1. Similarity between RM and RW problems

VSS design is carried out in two steps. On the one hand, the sliding surface $\sigma=0$ is chosen to fulfil control specifications such as dynamic behaviour, robustness to state disturbances and model uncertainties, etc. On the other hand, the inputs (u^+, u^-) and the switching logic are selected to enforce the state convergence towards $\sigma=0$ (Ryan & Corless, 1984).

During ideal SM, u switches at infinite frequency between u^+ and u^-. This discontinuous action produces the same dynamic behaviour as a fictitious continuous input signal, the so-called equivalent control $u_{\mathrm{eq}}(v, x_k)$ derived from the invariance condition ($\sigma=0,\ \dot{\sigma}=0$). During SM, the equivalent process input u_{eq} is constrained between the limit signals $u^- < u_{\mathrm{eq}} < u^+$ (Utkin et al., 1999). On the contrary, during RM the switch is fixed at one position and the process input is either u^+ or u^-. This means that the P–K loop is open and the process dynamics evolves independently of the controller. This lack of correspondence during RM can degrade the global performance of VSS. This degradation is worse when the state reaches $\sigma=0$ outside the sliding domain. When this occurs, the state trajectory cannot be confined to the surface and crosses it. Hence, the RM, i.e., the open-loop operation, is prolonged.

From the previous discussion, a noticeable correspondence arises between causes and effects of RM and RW problems. Actually, RW is an undesirable transient behaviour caused by the inconsistency between the process input and the controller state of continuous feedback systems subjected to restrictions.[1] Effectively, the system performs in open loop because of this inconsistency, possibly leading to large overshoots and long settling time (Peng, Vrančić, & Hanus, 1996; Kothare, Campo, Morari, & Nett, 1994). Moreover, similar to what happens in VSS, the controller design for constrained linear systems is commonly developed following a two-step procedure (Peng et al., 1996; Kothare et al., 1994). Firstly, a controller to guarantee the control requirements is designed ignoring the physical limitations. Then, the AW compensation is incorporated to the previous controller satisfying the following specifications:

(1) stability,
(2) correction only when the limitation is active,
(3) graceful degradation with respect to the unrestricted control system.

Based on the close connection between these problems, classical solutions and more recent progresses in the control theory of constrained linear systems can potentially be extended to improve the RM of VSS.

2.2. RM compensation scheme

In this note, the feedback correction block Λ drawn in Fig. 1 is proposed to improve the RM. This compensation approach closely follows the AW scheme encompassing most of the existing AW methods (see Kothare et al., 1994). Analogously, different RM algorithms obtained as a generalization of AW methods can be seen as particular designs of Λ. To assure the compensated controller $\hat{K}$ can also be realized as an LTI system, Λ is assumed causal and LTI. Based on the understanding that the sliding surface has been designed according to the control specifications, the correction of the state and output of K (ξ_1 and ξ_2, respectively) must only be active during RM, i.e.

$$\sigma(t)=0 \quad\Rightarrow\quad \xi(t)=0. \tag{2}$$

The sliding dynamics obtained by the discontinuous action, as well as by u_{eq}, can also be accomplished by a saturated actuator with gain $k\to\infty$ (Utkin et al., 1999). This allows defining, in the context of RM, a saturation error equivalent to the one used in all AW methods (Peng et al., 1996; Kothare et al., 1994)

$$e = \lim_{k\to\infty}\left(\sigma - \frac{u}{k}\right) = \sigma. \tag{3}$$

[1] Although RW is usually associated with the controller dynamics and actuator constraints, it may also be caused by slow or unstable dynamics of the process and its own constraints even when static controllers are used (Hippe & Wurmthaler, 1999).