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Anti-windup for marginally stable plants and its application to open water channel control systems ☆

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Abstract

Actuator saturation can have a significant impact on control system performance. In particular, when actuators saturate because of large initial condition mismatch at startup, or because of large disturbances, the controller can suffer from so-called integrator windup. This paper describes the application of recent anti-windup and bumpless transfer (AWBT) compensation techniques to the problem of open water channel control. This is nontrivial in light of the (marginally) unstable nature of uncontrolled open water channels, which for the purposes of controller design, can modelled as a concatenation of *integrators*, linked by saturation-prone gates used to regulate the flow of water. AWBT compensator design is considered within the context of both continuous- and discrete-time controllers and models. All simulation studies are carried out using an experimentally validated, high-fidelity model of the Haughton Main Channel in Queensland, Australia. The AWBT compensation schemes considered achieve excellent performance.

Keywords: Anti-windup; Bumpless transfer; Multi-variable control; Marginally stable system; Open water channels; LQ control; H_∞ loop shaping

1. Introduction

Fresh water is a scarce resource in many parts of the world today. As such, it is important for all water resources to be well managed. This is particularly relevant within the context of irrigation networks where water losses, due to inefficient management and control, can be very large. As the level of instrumentation and automation in irrigation networks increases, there is significant potential for reducing water losses via better prediction and control of the channels, see e.g. Malaterre and Baume, 1998; Mareels et al., 2005 for an overview.

Typically, irrigation channels are open water channels. Water levels and flows are controlled by gates located along the channel, as sketched in Fig. 1. The stretch of a channel between two gates is commonly referred to as a pool. Along a typical medium sized channel there can be as many as 20 to 30 gates and various offtake points to farms and secondary channels (see Fig. 2). Often the offtakes to the farms are gravity fed. In order to deliver water in this way, it is important to ensure that the water levels in the pools remain above certain critical levels. To this end, automatic controllers that impose gate positions on the basis of measured water levels can be employed. In particular, a control objective is to reject load disturbances due to offtakes. Since the dynamics of open water channels can be approximated well by linear models, linear control schemes are typically able to meet performance specifications under normal operating conditions (see, for example, Garcia, Hubbard, & de Vries, 1992; Malaterre & Baume, 1998; Malaterre, 1998; Schuurmanns, Hof, Dijkstra,

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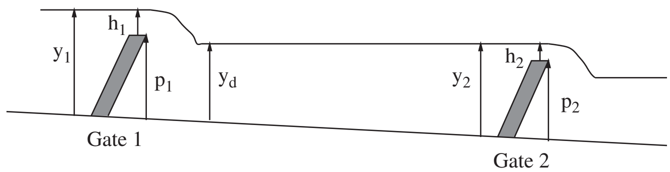

Fig. 1. Sketch of irrigation channel with gates.

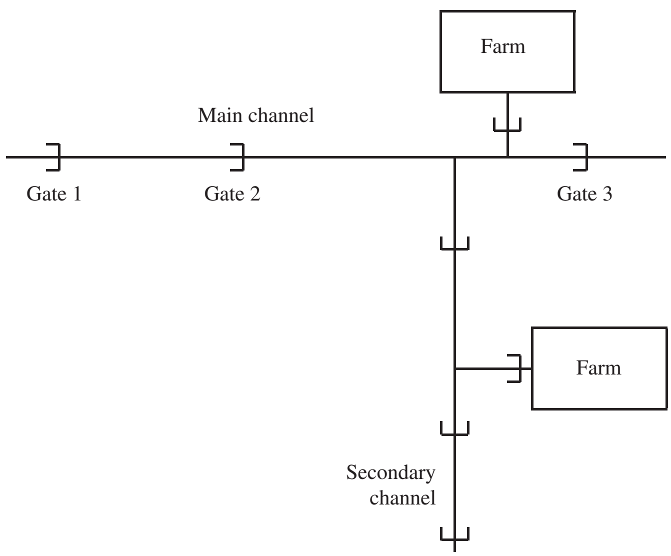

Fig. 2. Top of irrigation network.

Bosgra, & Brouwer, 1999; de Halleux, Prieur, Coro, d'Andrèa Novel, & Bastin, 2003; Litrico, 2002; Litrico, Fromion, Baume, Arranja, & Rijo, 2005; Ooi & Weyer, 2003; Weyer, 2002, 2003; Li, Cantoni, & Weyer, 2004; Li, 2006; Cantoni, Weyer, Li, Ooi, & Mareels, 2007, to appear.).

In open water channels, control authority is limited in that gate positions can only range from fully closed to fully open. This input saturation effect, which is not captured by the linear models often used to design automatic controllers, is especially significant in the following situations: during the startup of an automatic controller; in the presence of large off-takes (disturbances); and under low flow conditions, which typically occur overnight when there is low demand for water (in this case the gates operate close to the fully closed positions). When operating around the saturation limits, significant degradation in performance can be observed with respect to the designed linear behaviour. This can be mitigated via augmentation of a linear control scheme. In particular, given a linear controller that achieves desirable properties with a linear plant model, so-called anti-windup augmentation schemes such as the one shown in Fig. 3, can be employed to ensure that

(1) provided the controller output remains within the saturation limits, the (nonlinear) closed-loop response will coincide with the (linear) response without saturation—henceforth this is referred to as the "unconstrained response";
(2) when the saturation limits are exceeded for a period of time, the "unconstrained response" is recovered in a desirable manner.

Anti-windup augmentation has long been studied within the control community. Indeed, some of the earliest work dates back to the 1950s (Lozier, 1956). Since the 1990s, many advanced solutions to the problem have been proposed (see for example, Kothare, Campo, Morari, & Nett, 1994; Zheng, Kothare, & Morari, 1994; Park & Choi, 1995; Gilbert, Kolmanovsky, & Tan, 1995; Miyamoto & Vinnicombe, 1996; Teel & Kapoor, 1997; Edwards & Postlethwaite, 1999; Gilbert & Kolmanovsky, 1999; Shamma, 2000; Mulder, Kothare, & Morari, 2001; Zaccarian & Teel, 2002; Cao, Lin, & Ward, 2002; Grimm et al., 2003). In addition to recovering linear performance, anti-windup augmentation schemes can exhibit bumpless transfer properties, which is appealing when switching between manual and automatic control.

This paper addresses the anti-windup and bumpless transfer (AWBT) performance of the augmentation structure shown in Fig. 3, within the context of both continuous and discrete-time models of the plant and unconstrained controller. This is a nontrivial exercise in light of the fact that open water channels are marginally stable[1] systems (a pool is essentially an integrator since the rate of change in the volume of water is equal to the flow in minus the flow out) and the fact that a saturated system with poles on the imaginary axis cannot be exponentially stabilised globally (see Sontag, 1984, for example). The approach taken here corresponds to the anti-windup framework described in Teel and Kapoor (1997) (for the continuous-time case) and in Grimm, Teel, and Zaccarian, 2003 (for the discrete-time case) for general linear systems, and the recent bumpless transfer results of Zaccarian and Teel, 2005.

Briefly, the paper is structured as follows. Section 2 comments on the modelling of open water channels and presents both continuous-time and discrete-time linear models suitable for controller design. Section 3 describes an anti-windup technique in both continuous and discrete time. Finally, Section 4 reports on simulations of the closed-loop behaviour of the augmented closed-loop with an experimentally validated, high-fidelity model of an open water channel. Notation and symbols are defined in Table 1.

2. Models

In subsequent sections an anti-windup schemes for two controllers will be considered, one designed in continuous-time and the other in discrete time, for the Haughton main

[1] "Marginally stable" denotes a system which does not have any pole with positive real part and which has poles on the imaginary axis having multiplicity 1.