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Model predictive control based on an integrator resonance model applied to an open water channel

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ABSTRACT

This paper describes a new simplified model for controller design of open water channels that are relatively short, flat and deep: the integrator resonance model (IR model). The model contains an integrator and the first resonance mode of a long reflecting wave. The paper compares the integrator resonance model to the simplified models: integrator delay, integrator delay zero and filtered integrator delay and to the high-order linearized Saint-Venant equations model. Results of using the integrator resonance model in a model predictive controller applied in closed loop on a high-order non-linear Saint-Venant model of the first pool of the laboratory canal at Technical University of Catalonia, Barcelona are compared to the results of using the other simplified models in MPC. This comparison shows that the IR model has less model mismatch with the high order model regarding the relevant dynamics of these typical channels compared to the other simplified models. It is demonstrated that not considering the resonance behavior in the controller design may result in poor performance of the closed loop behavior. In order to demonstrate the validity of the simulation model used in this study, the controller using the IR model is also tested on the actual open water channel and compared to the results of the high-order non-linear Saint-Venant simulation model. The results of this comparison show a close resemblance between simulation model and real world system.

1. Introduction

In order to increase water delivery efficiency, throughout the world, control of open water channels such as irrigation canals is implemented, often referred to as canal automation. A common control configuration is distant downstream control where the water level h_2 downstream in the open water channel needs to be kept as close as possible to a setpoint by adjusting the flow Q_1 of the hydraulic structure upstream in the channel (see Fig. 1). For open water channels that are short, flat and deep this can be complicated due to the occurrence of resonances (Schuurmans, 1997). These resonances are badly damped long waves that reflect on the ends of the open water channel. Channels that are short, flat and deep have a small integrated friction force over the length of the pool, which means it is easy for waves to travel up and down the pool a number of times before settling. The characterization in short versus long, flat versus steep and deep versus shallow is hard to define in standard rules, due to the complexity of the dynamic behavior of open water channels. van Overloop (2006) attempts to capture the sensitivity for resonance waves as a function of length, width, friction coefficient, flow and average depth of an open water channel. Litrico and Fromion (2009) prove that resonance waves are also present in long, steep and shallow open water channels, but that they do not show up in measurements as they are damped significantly.

The first resonance mode, as depicted in Fig. 1, is troublesome for distant downstream control as its peak is in 180° phase lag with the control input. The gain margin criterion for designing feedback controllers dictates the controlled system gain at that frequency to be smaller than 0.5, in order to be robust against instability. Another explanation why it is hard to deal with this first resonance mode is that it does not make sense to decrease the flow Q_1, when the water level h_2 is higher than the setpoint, because in fact the flow at the upstream side of the pool is already lower due to the oscillation and needs not be lowered more.

In order to avoid unstable closed loop control, there are three ways to deal with the resonance in the controller design. First, the resonance can be accepted and, consequently, obeying the gain margin criterion will result in a low performing closed loop behavior. Second, the resonance can be filtered before it enters the controller, allowing for a higher performance. In this case, the resonance is present, but the controller does not react to it in order

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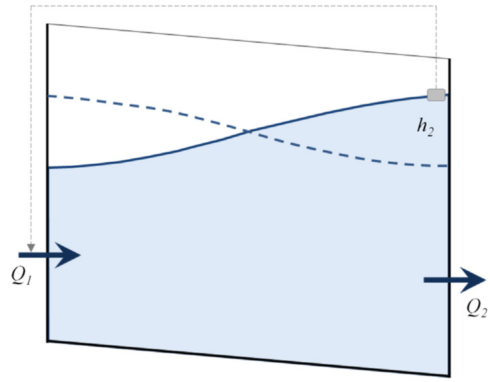

Fig. 1. Resonance-sensitive open water channel including distant downstream control loop.

to avoid instability. Third and the last, the resonance can be included in the controller model, which means the controller avoids triggering the resonance mode as much as possible. In this paper, these different ways of controller design are analyzed and evaluated on an actual open water channel that is very sensitive to resonance waves. The innovative aspect of this research is that it proposes a new simplified model that models the first resonance mode as part of the controller model: the integrator resonance model (IR model).

2. Simplified models of open water channels

In order to develop controllers for open water channels, simplified models need to be developed. Many standard controller design algorithms for feedback and feedforward control require low order linear models (Vandevegte, 1990). Low order and linear models are also important for real-time optimizing controllers, such as model predictive control, in order to achieve tractability and convexity (Camacho & Bordons, 2004).

Over the past two decades, in the field of control of open water channels, various types of simplified models have been developed. Schuurmans (1997) proposes the integrator delay (ID) model, which consists of a delay part describing the upstream uniform flow part and an integrator describing the downstream storage volume of which the water level needs to be kept at setpoint. This model describes the low frequency behavior accurately, but does not contain resonance modes. For long, steep and shallow open water channels, this model performs excellent. By simplifying the linearized Saint-Venant equations, Litrico and Fromion (2004) arrive at the conclusion of adding a zero to the ID model in order to model the high frequency behavior. This integrator delay zero (IDZ) model captures the average behavior of the resonances, but unfortunately not the peaks of which the first one is so important for stable controller design of distant downstream control. Weyer (2001) attempts to capture the first resonance by proposing a third-order model with delay and fitting this model to measured data using system identification algorithms. In van Overloop et al. (2010) it is demonstrated that this procedure may result in the underestimation of the first resonance peak due to the influence of the second and even higher resonance modes that are present in the measurements and may not be completely filtered out. The system identification algorithm tries to fit the resonator to be optimal for both the first peak and the higher harmonics that are remaining in the signals, reducing the value of the identified peak of the important first resonance mode. A simplified model for open water channels that focuses on the always present integrator and only the first resonance mode has not been assessed in the literature before.

3. Open water channel dynamics of resonance-sensitive open water channels

The Saint-Venant equations, calibrated on the friction parameter, describe the dynamic behavior of water flow in an open water channel accurately (Chow, 1959). A discretized and linearized Saint-Venant model of a short, flat and deep pool presented in the frequency domain demonstrates clearly the integrator at low frequencies and the resonance peaks at higher frequencies (see solid line in Fig. 2). In van Overloop et al. (2010) the Laplace transfer function from an inflow Q_1 to the downstream water h_2 is derived. This transfer function is a third-order model without time delay consisting of an integrator with a gain of the reciprocal of the storage area A_s and a damped oscillator characterized by the natural frequency ω_0 and magnitude peak M of the first resonance

$$H_{IR}(s) = \overbrace{\frac{1}{A_s \cdot s}}^{\text{Integrator}} \cdot \overbrace{\frac{{\omega_0}^2}{s^2 + \frac{s}{A_s \cdot M} + {\omega_0}^2}}^{\text{Resonance}} \tag{1}$$

The parameters' storage area A_s, the natural frequency ω_0 and magnitude peak M of the first resonance of this model structure can be estimated using different procedures, e.g. from a step response, system identification using a chirp signal or a random binary signal around an initial estimate of the natural frequency. An important notice is that this model is a linearization of the non-linear Saint-Venant equations, so the parameters are different in different working points (see for example Table 1). The most important variables that determine the working points are the

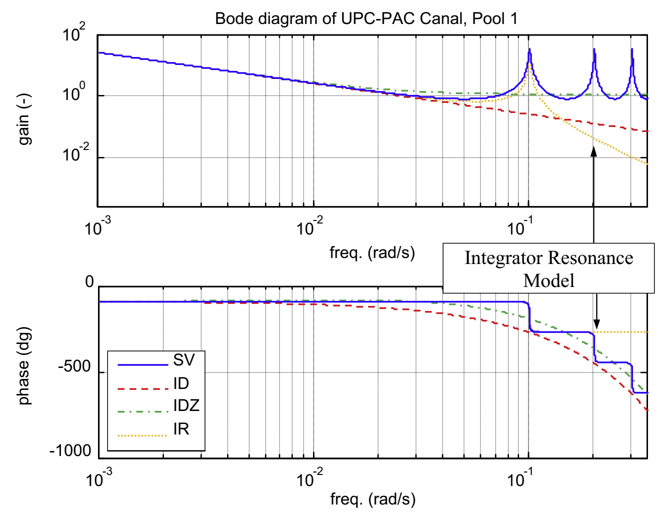

Fig. 2. Bode diagram of high-order linearized Saint-Venant model (solid line), integrator delay model (dashed line), integrator delay zero model (dash dotted line) and integrator resonance model (dotted line) modeling the laboratory open water channel.

Table 1
Properties of the first resonance of the first pool of laboratory canal UPC-PAC.

Flow (l/s)	Frequency ω_0 (rad/s)	Magnitude M
10	0.1011	35.09
30	0.1011	11.77
50	0.1010	7.11
70	0.1008	5.14
90	0.1006	4.05
110	0.1003	3.37
130	0.0999	2.91
150	0.0997	2.59