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Detection of Oscillatory Control Loops in Irrigation Channels

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Abstract:
In this paper the algorithm for detection of oscillatory control loops developed in Hägglund (1995) is applied to irrigation channels. The water levels in irrigation channels are controlled using mechanical gates. The controller configuration is a decentralized distant downstream scheme where a gate controls the water level upstream of the next downstream gate. The controller is a PI controller augmented with a low pass filter together with a feedforward term from the downstream gate. The algorithm is applied to real data from six consecutive reaches of an irrigation channel, and it detected the control loops that gave oscillatory response. Furthermore, due to the decentralized configuration, one is also able to localize the cause of the oscillation. Given that there can be many control loops in a channel network, the ability to localize the cause of an oscillation speeds up the trouble shooting process. However, care must be taken in choosing the thresholds in the algorithm in order to avoid frequent false alarm.

Keywords: Performance monitoring of control loops, Oscillation, Control systems, Environmental systems, Irrigation channels.

1. INTRODUCTION

The UN (United Nations) world water development report Water Report (2003) states that the Earth is facing a serious water crisis. Recently, in Water Report 2 (2006), it is estimated that water globally required for agriculture in 2025 is in the order of 600km^3, which is more than the estimated requirement for all domestic uses. It is not always the supply of water, but the ability to fully and efficiently utilize the available quantities, which is the problem. It is therefore important to manage the water resources well and minimize the losses. This applies particularly to networks of irrigation channels, where huge amounts of water are wasted due to poor management and control. These losses can be reduced by improving the control of the water levels in the channels, and control of irrigation channels is an area which attracts increased attention, see e.g. Malaterre and Baume (1998) and the references therein, Schuurmans et al. (1999), Gomez et al. (2002), Weyer (2002), de Halleux et al. (2003), Litrico and Pomet (2003), Weyer (2003), Litrico and Fromion (2003), Ooi and Weyer (2003), Dulhoste et al. (2004), Mareels et al. (2005),Weyer (2006a), Litrico et al. (2007), Cantoni et al. (2007) and Ooi and Weyer (2008). After a controller is designed, the natural next step is to assess the performance of the closed loop system with the designed controller. Well tuned controllers lead to improved water management and reduced wastage, but the undesired effect of a badly tuned controller will propagate through the channel network and it is therefore important to monitor the performance of the controllers and isolate and retune those which causing unwanted behavior such as large oscillations.

Performance monitoring or assessment of control loops is widely recognized as an important issue in many industries, particularly within the area of process control, see e.g. Harris (1996), Huang and Shah (1999), Paulonis and Cox (2003), Hoo et al. (2003), Ooi and Weyer (2005), Zhang and Weyer (2005) and Thornhill and Horch (2007). Poorly performing control loops cause undesirable consequences such as wastage of raw material which will increase the production cost, and significant improvement can be achieved if the poorly performing control loops are detected early.

For a network of irrigation channels, the operators may have to monitor every controlled water level in order to detect deterioration of closed loop performance. To assist the operators, alarms are usually raised when water levels fall outside specified limits, i.e. when the water level is too high or too low. However, there are many control loops in a network of irrigation channels, and it is very time consuming and even difficult to monitor each and every control loop manually. In addition, automatic design routines such as those in Ooi and Weyer (2008) or Ooi and Weyer (2003) were developed with the purpose of easing and speeding up the design of large number of controllers. It would be in conflict with this purpose if one needs to check the performance of each control loop manually. It is therefore desirable to have performance monitoring tools that evaluate the performance of every single control loop and inform the operator of any badly performing loops.

Due to the fact that experimental access is limited, the performance monitoring tool should be able to detect deterioration of closed loop performance using data available from normal day to day operation. The two most common effects of badly tuned controllers in irrigation channels are sluggishness and oscillations. The method for detection of sluggish control loops developed in Hägglund (1999) has been considered in Ooi and Weyer (2005) and the results are promising. However, the sluggish detection algorithm is unable to distinguish between a well tuned and an oscillatory control loop in irrigation channel, see Hägglund (1999) and Ooi and Weyer (2005) for the particular case of irrigation channels. Hence, in this paper, detection of oscillatory control loops in irrigation channels is considered. The algorithm proposed in Hägglund (1995) and Hägglund (2005) is considered.

The paper is organized as follows. In Section 2, a description of the irrigation channel is given. In the following section, the models and the designed controllers are given. A review of the detection algorithm is given in Section 4. In Section 4.2, the algorithm is applied to operational data from six consecutive pools of an irrigation channel. Concluding remarks are given in Section 5.

2. CHANNEL DESCRIPTION

The channel considered in this paper is the Coleambally Channel Number 6 (Coly6) in New South Wales, Australia. Figure 1 shows a schematic top view of the channel.

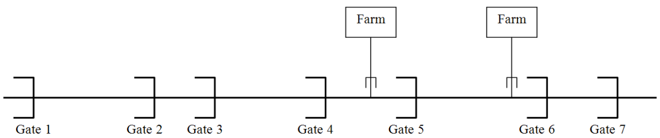

Fig. 1. Topview of Coly6 with Gates 1 to 7 (not to scale).

A stretch of channel between two gates is referred to as a pool. The pools are named according to the upstream gate, i.e. the pools in Figure 1 are Pools 1 to 6. The channel is automated with overshot gates as shown in Figure 3 where y_i and p_i are the upstream water level and the position of gate i (i =1, ..., 7) respectively, and h_i is the head over gate i which is the height of water above the gates.

Fig. 2. Photo of Gate 5.

There are two gates at each site as shown in Figure 2. Both gates operate in parallel, i.e. they always have the same position. The water levels and gate positions are the measured variables. Water levels are measured using submersible level pressure sensors and gate positions are measured based on the length of the steel cable between the gates and the motors that move the gates. The head over gate is computed as $h_i = y_i - p_i$. As channels are located in rural areas, electric power is supplied by solar panels and data communication takes place via a radio network, see Figure 2. More details on the infrastructure is given in Mareels et al. (2005).

3. MODELS AND CONTROLLERS

In this section, the models and the controllers are presented.

3.1 Models for control design

The model is obtained by considering a simple volume balance, see Weyer (2001) and Ooi et al. (2003)

$$\dot{y}_{i+1}(t) = c_{i,\text{in}} h_i^{3/2}(t - \tau_i) + c_{i+1,\text{out}} h_{i+1}^{3/2}(t) + d_i(t) \quad (1)$$

$d_i(t)$ represents offtakes to farms and side channels. A time delay τ_i has been introduced to take into account the time between water passes the upstream Gate i and the effects reaches the downstream gate where y_{i+1} is measured.

By replacing the derivative $\dot{y}_{i+1}(t)$ by the difference $(y_{i+1}((k+1)T) - y_{i+1}(kT))/T$ where T is the sampling interval, the discrete time model

$$y_{i+1}((k+1)T) = y_{i+1}(kT) + Tc_{i,\text{in}} h_i^{3/2}((k - \tilde{\tau}_i)T) + Tc_{i+1,\text{out}} h_{i+1}^{3/2}(kT) + Td_i(kT) \quad (2)$$

is obtained. The above models are, as all models are, only approximations of the physical reality. However, the models represent the relevant dynamics for control well as demonstrated in Weyer (2001),Weyer (2002),Ooi et al. (2003),Weyer (2006a). The unknown parameters are estimated using data simulated by the St. Venant equations, see Ooi and Weyer (2008) for details.

3.2 Controller configuration

The feedback controllers considered are PI controllers augmented with lowpass filters, i.e.

$$C_i(s) = \frac{K_i(1 + T_{i,c}s)}{T_{i,c}s} \cdot \frac{1}{1 + T_{i,f}s} \quad (3)$$

and this combination is referred as a PIL controller. The main objective of the controller is to reject load disturbances which are offtakes of water to farms from the pools, and integral action is required in order to achieve this. There are waves present in the channel and the lowpass filter is introduced in order to ensure a low gain at the wave frequency. The controller configuration considered is the distant downstream decentralized configuration as shown in Figure 3.

Introducing the new input variables $u_i(t) = h_i^{3/2}(t)$ the model (1) can be written as

$$\dot{y}_{i+1}(t) = c_{i,\text{in}} u_i(t - \tau_i) + c_{i+1,\text{out}} u_{i+1}(t) + d_i(t) \quad (4)$$

The control actions at the downstream gate $u_{i+1}(t)$ act as a disturbance on Pool i. However, measurements of $u_{i+1}(t)$ are available, and its effects can be compensated for by feedforward as shown in Figure 3. The feedforward path is given by

$$G_i(s) = K_{\text{ff,i}} F_i(s) c_{i+1,\text{out}} / c_{i,\text{in}}$$

where a lowpass filter $F_i(s)$ has been introduced in order to make sure that waves are attenuated. The gain has been reduced

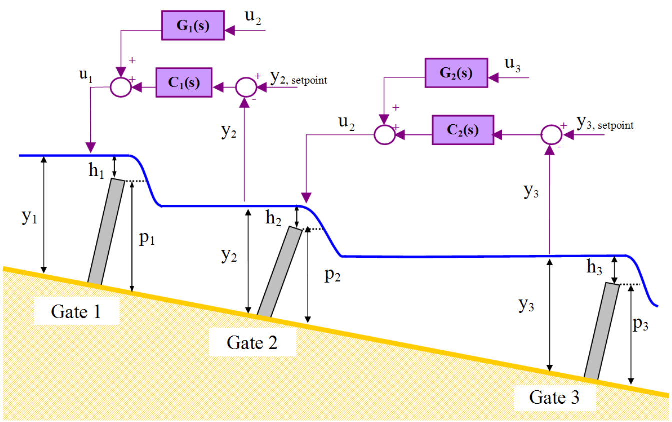

Fig. 3. Side view of Pool 1 and 2 with distant downstream decentralized controllers with feedforward.

Pool (i)	Length	$T_{i,c}$	$T_{i,f}$	K_i	FF
1	1082m	170.41	9.97	1.48	0.98
2	413m	55.74	3.26	1.07	0.75
3	1014m	86.58	7.60	1.14	0.56
4	943m	96.54	8.47	1.26	0.75
5	1275m	113.60	9.97	1.29	0.75
6	900m	113.00	9.90	1.30	0.75

Table 1. Controller parameters of Pools 1 to 6 together with the length of the pools.

to $K_{\text{ff},i}$ in order to avoid large overshoots since the feedforward path cannot compensate for the time delay τ_i. As in Weyer (2002) $F_i(s)$ is a second order Butterworth filter with cutoff frequency around half the wave frequency, and $K_{\text{ff},i} = 0.75$.

To summarize, the controller equation is given by

$$U_i(s) = C_i(s)(Y_{i+1,\text{setpoint}}(s) - Y_{i+1}(s)) + G_i(s)U_{i+1}(s) \tag{5}$$

where $u_i(t) = h_i^{3/2}(t)$, and $U_i(s), U_{i+1}(s), Y_{i+1}(s)$ and $Y_{i+1,\text{setpoint}}(s)$ are the Laplace transform of $u_i(t), u_{i+1}(t)$, $y_{i+1}(t)$ and $y_{i+1,\text{setpoint}}(t)$ respectively.

The controllers of Pool 1 to 5 were tuned using an automatic tuning routine, see Ooi and Weyer (2008) for details, and the results are given in Table 3.2. The feedforward gain $FF = K_{\text{ff},i}\frac{c_{i+1,\text{out}}}{c_{i,\text{in}}}$. The controller of Pool 6 was tuned manually.

4. DETECTION OF OSCILLATORY CONTROL LOOPS

4.1 Review of the proposed algorithm

The algorithm to detect oscillations in control loops proposed in Hägglund (1995) was developed based on a study of the magnitude of the integrated absolute error (IAE) between successive zero crossings of the setpoint error, $e_{i+1}(t) = y_{i+1,\text{setpoint}}(t) - y_{i+1}(t)$, i.e.

$$IAE = \int_{t_{k-1}}^{t_k} |e_{i+1}(t)|dt \tag{6}$$

where t_{k-1} and t_k are two consecutive instances of zero crossings.

The magnitude of $e_{i+1}(t)$ will be small for a well tuned controller and the times between zero crossings are relatively short which gives small IAE values. On the other hand, IAE will become large when a load disturbance occurs which causes $|e_{i+1}(t)|$ to increase and a relatively long period without zero crossings occurs. Hence, if the IAE computed is larger than a certain limit IAE_{lim}, it is likely that a load disturbance has occurred. The load detection procedure can be summarized as follows (see Hägglund (1995) for details):

(1) Choose an acceptable peak to peak oscillation amplitude a.
(2) Calculate $IAE_{lim} = \frac{2a}{\omega_i}$, where $\omega_i = \frac{2\pi}{T_{i,c}}$ and $T_{i,c}$ is the controller integrator time (see equation (3)).
(3) If the IAE computed using equation (6) is larger than the preset limit IAE_{lim}, one concludes that a load disturbance has occurred.

An oscillatory response will cause the setpoint error signal to behave like a wave. This will be detected as a sequence of load disturbances. If the number of detected load disturbances is more than a user chosen limit n_{lim} over a supervisor time T_{sup}, then one can conclude that an oscillation is present. The supervisor time is computed as

$$T_{sup} = 5\, n_{lim} T_{i,c} \tag{7}$$

As mentioned in Hägglund (1995), the above procedure for detection of an oscillatory response is quite ineffective since a time label is required for each and every load detection. Instead of cumulatively adding the number of load disturbances, an alternative procedure is derived in Hägglund (1995) which apply an exponential weighting to the rate of load detection, x. The procedure is updated every sampling instant T as follows

$$l = \begin{cases} 1, & \text{if a load is detected} \\ 0, & \text{otherwise} \end{cases}$$

$$x = \gamma x + l; \quad \text{where } \gamma = 1 - \frac{T}{T_{sup}} \tag{8}$$

if $x \geq n_{lim}$ then conclude that an oscillation is present.

4.2 Application in irrigation channels

Here the oscillation detection algorithm is applied to operational data from Pool 1 to 6. The water levels are shown in Figure 4 together with their setpoints of 1.450m, 1.510m, 1.554m, 1.525m, 1.600m and 1.445m for Pool 1 to 6 respectively. The controllers parameters are given in Table 3.2. The sampling period is 1 minute, i.e. $T = 1$. In order to reduce the wear and tear on the gates, a deadband, $\bar{d}$ was imposed on the gate movement. This means that if the new gate position given by the controller was less than $\bar{d}$m away from the current one, the gate did not move. The dead bands are set by operators and they are in the order of a few centimeters and do vary with flow conditions. The oscillation detection procedure is carried out by computing IAE and checking if the frequency of load disturbances detection is more than the allowed limit using the procedure (8). Figures 5 to 10 show the IAE, IAE_{lim}, the rate of load detection x and n_{lim} for Pool 1 to 6 respectively. Table 4.2 shows the user chosen parameters a and n_{lim} in the algorithm together with the time when an oscillation (if any) was first detected.

4.3 Discussion

From Figures 5 to 10, one can see that the algorithm detected the oscillations which occurred in Pool 1 to 5 (since the rate $x > n_{lim}$) and no oscillation was detected in Pool 6 (since the rate $x < n_{lim}$). The actual oscillations are easily observable

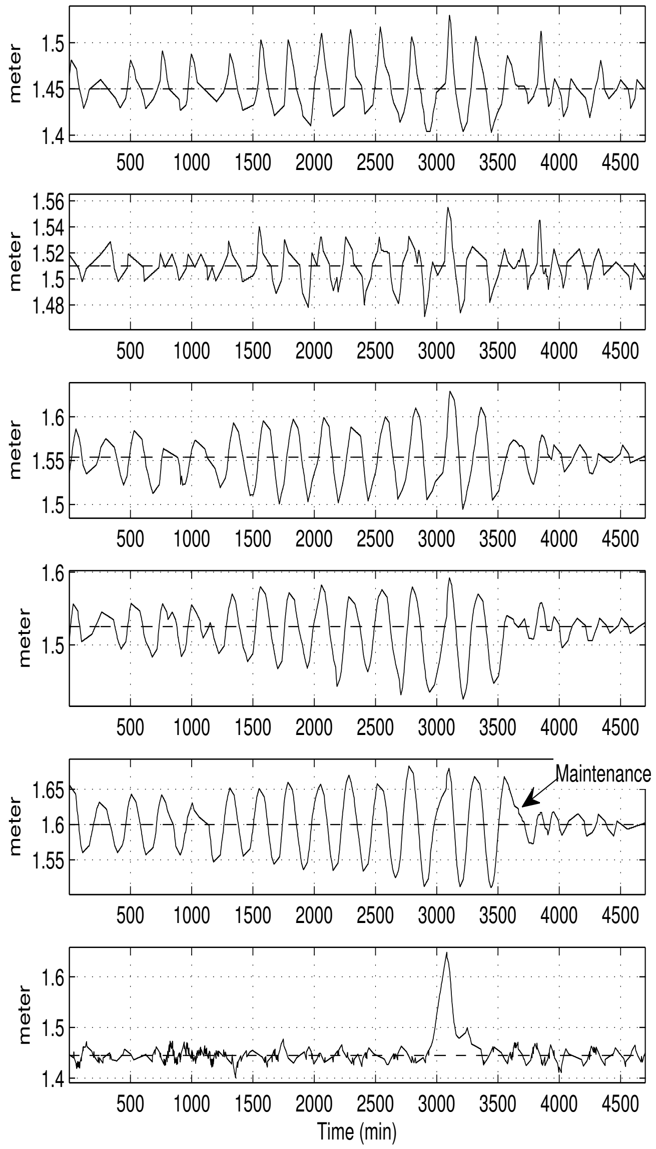

Fig. 4. Water levels of Pool 1 (top) to 6 (bottom) together with setpoints (dashed line)

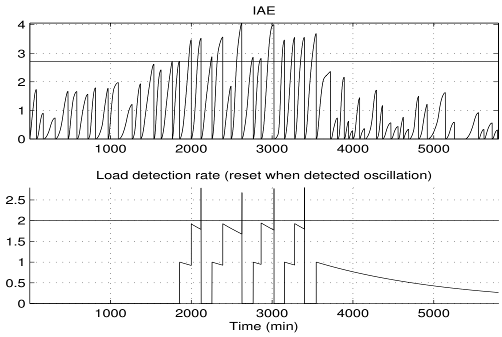

Fig. 5. Pool 1: IAE and rate of load detection x

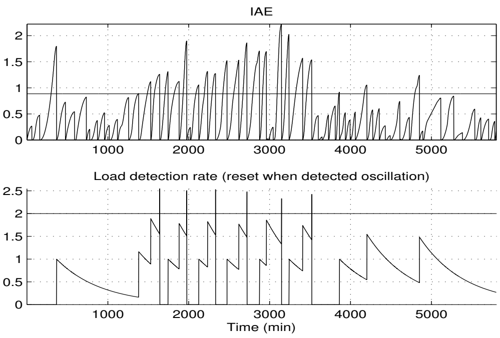

Fig. 6. Pool 2: IAE and rate of load detection x

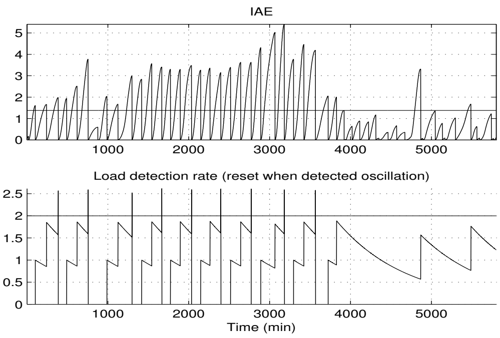

Fig. 7. Pool 3: IAE and rate of load detection x

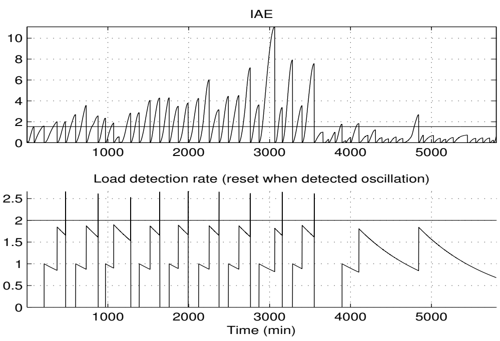

Fig. 8. Pool 4: IAE and rate of load detection x

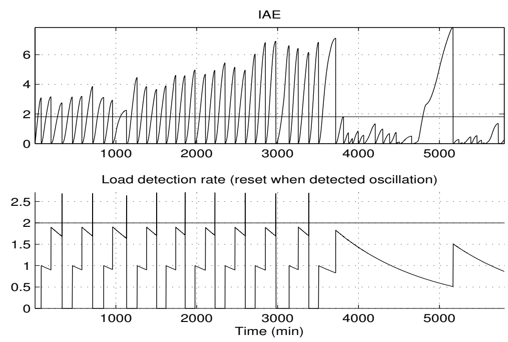

Fig. 9. Pool 5: IAE and rate of load detection x

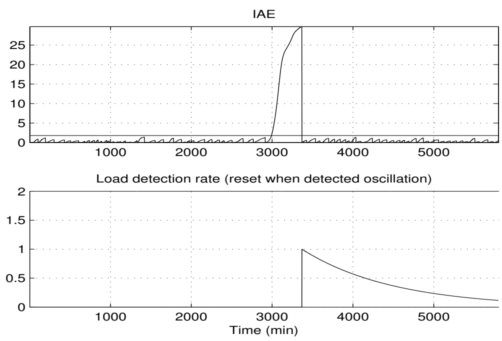

Fig. 10. Pool 6: IAE and rate of load detection x

Pool (i)	a	n_{lim}	T_{detect}
1	0.05	2	2121min
2	0.05	2	1642min
3	0.05	2	387min
4	0.05	2	477min
5	0.05	2	335min
6	0.05	2	N/A

Table 2. User chosen parameters a and n_{lim}, the time when the oscillation was first detected T_{detect}.

in Figure 4. In fact, the oscillations had been present for a long time without being discovered as there was no oscillation detection algorithm implemented in the system. Hence, the maintenance was only carried out at around time 3580min when the operators realized that the water levels oscillated with a peak-to-peak amplitude of more than 15cm.

The control engineer investigated the oscillating loops and found that one of the controller parameters for Pool 5 $T_{5,f}$ was wrong. It was ten times larger than what it was supposed to be. Hence, at time 3560min, the controller was switched to flow mode, i.e. gate 5 maintained a fixed flow rate. This is marked with 'Maintenance' in Figure 4. The correct value $T_{5,f} = 9.97$ as in Table 3.2 was entered, and the controller for Pool 5 was switched back on. From Figure 4, one can clearly see that after the maintenance, the responses were much better. Moreover, after the maintenance was carried out, the algorithm does not detected any oscillating loop, i.e. no false alarm, since from Figures 5 to 10 $x < n_{lim}$ for all pools after time 3570min. From a practical point of view it is very important to avoid false alarms since the operators will stop using the system if there are too many false alarms .

If the online oscillation detection algorithm had been implemented, the algorithm would have detected an oscillating control loop in Pool 5 at 335min as shown in Table 4.2, and an alarm would have alerted the operators. The problem could then have been investigated and fixed at a much earlier time. Due to the distant downstream decentralized controllers configuration, disturbances only propagate from downstream pools to upstream pools. Hence, by applying the algorithm to all the pools in the channel, one will be able to localize the cause of the oscillation. From Table 4.2, one can clearly see that there are oscillatory responses detected in Pool 1 to 5, but not in Pool 6. Hence, one will quickly narrow down the cause of the oscillation to either a badly tuned controller in Pool 5 or an aggressively tuned controller of Pool 6 causing large gate movements which set up the oscillations in Pool 5. Hence, one can now concentrate the diagnosis on only two controllers instead of 11 (Coly 6 has a total of 11 gates), simplifying and speeding up the diagnosis process significantly.

One may argue that a T_{detect} of more than five hours seem a bit slow, but if one looks closely at Figure 4, one will see that the period of the oscillations are quite large (around 250min) and therefore a detection of the oscillations in about 5 hours is in fact fast.

Of course, the detection time, T_{detect} can be decreased by adjusting the user chosen parameters in the algorithm. However, this may cause false alarm. For example, if n_{lim} is set to 1, T_{detect} of Pool 5 becomes 119min. However, the detection algorithm will give a false alarm at time 5169min in Pool 5 as well as false alarms in Pool 2 to 4 at around time 5000min. On the other hand, if $a = 0.03$ the algorithm is able to detect oscillating loops earlier in Pools 1, 2 and 4, but not in Pools 3 and 5. However, this will also cause false alarms in most of the pools. The reason that T_{detect} of Pools 3 and 5 remain unchanged with a smaller a is because load disturbances are detected almost immediately, i.e. $IAE > IAElim$ right at the start. Unless, the water levels oscillate with a higher frequency, one will not be able to decrease T_{detect} in Pools 3 and 5.

The choices of $n_{lim} = 2$ and $a = 0.05$ correspond to a maximum deviation in water levels from setpoints of 2.5cm before the algorithm treats it as a load disturbance, and the maximum number of load disturbances allowed within the supervisor time T_{sup} is three before the algorithm concludes that an oscillatory control loop is present. $a = 0.05$ is a reasonably choice in this case since in practice a deviation from the setpoint of 2.5cm is allowed. Even though $n_{lim} = 2$, due to the exponential weighting used in the computation of the load detection rate x (see (8)), the actual number of load disturbances that occur is 3 before $x \geq n_{lim} = 2$. From these considerations, $n_{lim} = 2$, i.e three load disturbances, is a reasonably choice as in general the first two deviations are expected. The first deviation corresponds to the offtake and the second one is maybe due to an overshot, hence in practice one would allowed for two deviations larger than 2.5cm before an alarm is raised.

From the above results, it is clear that the oscillatory control loop detection algorithm proposed by Hägglund (1995) works well in the irrigation channel considered. The data material presented here is limited and more data is required to determine if user chosen parameters in the algorithm can be found such that the algorithm returns sensible results for a broad range of channel types and operational conditions. A great advantage of the method is that it is simple and that it can be implemented locally at each gate in a decentralized fashion. However, care must be taken in the selection of the user chosen parameters since badly chosen parameters can degrade the performance by causing frequent false alarms. A more complex model based approach to performance monitoring of irrigation channels is given in Zhang and Weyer (2005).

5. CONCLUSION

In this paper, the oscillation detection algorithm developed in Hägglund (1995) is applied to an irrigation channels with six consecutive pools. The algorithm worked well for detection of oscillatory control loops and it was able to detect oscillations caused by a wrongly tuned controller. Furthermore, due to the distant downstream decentralized controller configuration, where disturbances only propagate from downstream pools to upstream pools, the cause of the oscillations can be localized to either the controller of the upstream gate or the controller of the downstream gate of a pool. As there can be many gates, and hence many control loops in a channel, it can be very time consuming task if one needs to diagnose each and every controller manually whenever there is an alarm due to oscillations. Therefore, the ability to localize the cause has simplified and accelerated the trouble shooting process.

A great advantage of the method is that it is simple and that it can be implemented locally at each gate in a decentralized fashion. However, care must be taken in selecting the user chosen parameters in the algorithm in order to avoid false alarms.

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