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MODEL PREDICTIVE CONTROL OF WATER LEVELS IN A NAVIGATION CANAL AFFECTED BY RESONANCE WAVES

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In order to operate navigation canals several requirements need to be met: keeping minimum ecological flow, flood protection, but also for safe operation the water level has to be kept within a certain range around the normal navigation level. The water level is disturbed by several factors: known (measured tributaries) and unknown (unknown tributaries, rain) inputs. However, the most important one is the operation of the locks. If the navigation reach is bounded by locks that overcome large elevation differences, their operation can create big disturbances. These locks should be operated fast enough to allow the crossing of several boats, however the faster they are operated the bigger waves they create. These waves can lead to large deviations from the normal navigation level. Moreover, they can travel several times back and forth before they attenuate, especially in cases of low base flow, high water level, and smooth surface ï these are typical characteristics of a lot of navigation canals. Therefore, when the water level is controlled actively (e.g. by the gates located next to the locks) the effect of these waves should be taken into account. In this paper we present a method for a centralized control of water levels. This method decreases the effect of the waves. The method is presented on the example of the Cuinchy-Fontinettes case study.

INTRODUCTION

Navigation requires the water level to stay in a certain range. The situation of interest is when navigation canals are interconnected by locks that overcome large differences of water levels. The lock operations can cause a disturbance in the water level. They generate a wave that travels back and forth in the canal before it attenuates. This phenomenon is especially strong in the case of flat canals, such as navigation canals. The above described phenomenon is called resonance and is described in [7] and [8], and later studied in depth in [10] and [11].

The goal of this work is to maintain the water level of a canal within the range allowed for navigation affected by the resonance waves generated by the lock operations. The choice of control action is model predictive control (MPC). It is commonly used for different type of water systems [5], [6], [12], [13], [9]. MPC is suitable to control the navigation reach due to its ability of using internal model, treating known and unknown disturbances tackling constraints in the input.

The integrator resonance model has been developed by van Overloop [11] and applied to a laboratory irrigation canal in [15]. In this work the model will be further developed to be applied to a reach that has an inflow in the middle.

This work is structured as follows: first the problem is described through a case study, then the resonance model is introduced. Following the application of the model of the case is described with the controller development. Finally the results of the controller for known and unknown disturbances are shown and the work is concluded.

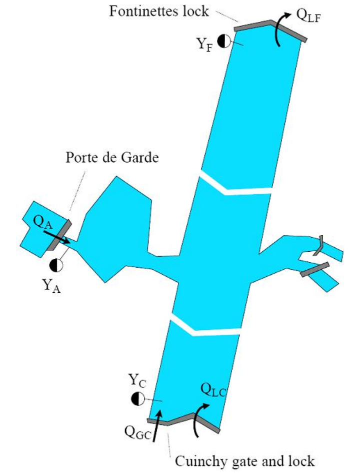

Figure 1. The schematics of the CFR

CASE STUDY: THE CUINCHY-FONTINETTES REACH

Description of the Cuinchy-Fontinettes Reach

The Cuinchy-Fontinettes Reach (CFR) is bounded by upstream the lock of Cuinchy (with discharge Q_{LC}) and downstream by the lock of Fontinettes (with discharge Q_{LF}) (Figure 1). The water level is measured (and to be maintained at *19.52m*) at three locations: (1) upstream, at Cuinchy (Y_C), (2) in the middle of the reach, at Aire (Y_A) and (3) in the downstream and at Fontinettes (Y_F). There are two control action variables (control flows) to achieve this: (1) upstream, the gate of Cuinchy (Q_{GC}) and (2) in the middle of the reach the gate of Aire (Q_A). These control actions are limited:

$$0 \leq Q_{GC}(t) \leq 10\left[m^3/s\right] \qquad (1)$$

$$-7 \leq Q_A(t) \leq 7\left[m^3/s\right]. \qquad (2)$$

because of the physical constraints of the system. The transfer functions between the inputs and the outputs are the following:

$$\begin{pmatrix} Y_C \\ Y_A \\ Y_F \end{pmatrix} = \begin{pmatrix} G_{CC} & G_{AC} \\ G_{CA} & G_{AA} \\ G_{CF} & G_{AF} \end{pmatrix} \begin{pmatrix} Q_{GC} \\ Q_A \end{pmatrix}. \qquad (3)$$

where Q_{CG} is the upstream flow (at Cuinchy), Q_A is the flow in the middle of the reach (at Aire), and Y_C is the upstream water level (Cuinchy), Y_A is the intermediate water level (Aire) and Y_F is the downstream water level (Fontinettes). The matrix of Eq. (3) contains the corresponding transfer functions between the discharges and the water levels. The water levels and discharges are expressed as relative to a nominal steady state. For example:

$$Y_C(t) = y_C(t) - Y_{C0} \tag{4}$$

where $y_C(t)$ is the absolute water level and Y_{C0} is the water level belonging to the steady state where the equation was linearized. In case of the CFR this equilibrium state is the Normal Navigation Level, *19.52 m* and the steady state discharge is $0.6\ m^3/s$.

Table 1: The geometrical parameters of the CFR

Length, L (km)	L_{CA} (km)	L_{AF} (km)	Width (m)	Depth (m)	Manningôs co. (-)	Discharge (m^3/s)
42.3	28.7	13.6	52	3.8	0.35	0.6

MODELING

Most models canal control, just like the Integrator Resonance model, describe the transfer functions between the upstream and downstream water levels and discharges (in this case G_{CC}, G_{CF}, G_{AA}), however the transfer functions for an inflow that is located in the middle of the canal reach are not described yet. We present the extension of the model for an input flow that is located in the middle of the reach in order to be able to express transfer functions G_{AC}, G_{CA} and G_{AF}.

The Integrator Resonance model

The Integrator Resonance (IR) model was developed especially for canals affected by resonance by van Overloop [11]. The transfer functions of the IR model are given for the effect of the upstream and the downstream discharge on the downstream water level in [11] and [14]. In some cases, there can be an additional source of discharge or offtake between the upstream and the downstream end of the reach. In case of irrigation canals, this offtake is often located at the downstream end and can be modeled as the same effect as the downstream discharge. However, when this additional discharge source is located far from the downstream (and the upstream) end of the canal its modeling is not so straightforward.

The transfer function between the upstream discharge and the downstream water level and the transfer function between the downstream discharge and the downstream water level has the same denominator, they are the same wave, but with a phase difference of ´ . The discharge entering in the middle of the canal can be expressed also as a wave and an integrator. The gain of the integrator should be the same: the discharge feeding the canal that acts at low frequencies as tank and the gain of the integrator is the surface of the reach. The frequency and the peak of the resonance wave should also be the same, since it is the same wave travelling through the whole canal reach, and the frequency is determined by its travel time. Hence the only difference between the transfer function of the upstream, downstream and middle discharge and the downstream water level is the phase of the wave. The general formula for a transfer function between the downstream water level and a discharge source located at any place in the reach is written as:

$$g(s)=\frac{p_1 s^2+p_2 s+p_3}{A_s s^3+\frac{s^2}{Mr}+A_s\omega_0{}^2 s} \tag{5}$$

$$p_1=\frac{1-\frac{\omega_0\zeta\sin(p)}{\sqrt{1-\zeta^2\omega_0}}-\cos(p)}{A_s} \tag{6}$$

$$p_2=2\omega_0\zeta\frac{1-\frac{\omega_0\zeta\sin(p)}{\sqrt{1-\zeta^2\omega_0}}-\cos(p)}{A_s}+\frac{\omega_0{}^2}{A_s}\frac{\sin(p)}{\sqrt{1-\zeta^2\omega_0}} \tag{7}$$

$$p_3=\omega_0{}^2\frac{1-\frac{\omega_0\zeta\sin(p)}{\sqrt{1-\zeta^2\omega_0}}-\cos(p)}{A_s}+\frac{\omega_0{}^2}{A_s}\left(\frac{\omega_0\zeta\sin(p)}{\sqrt{1-\zeta^2\omega_0}}+\cos(p)\right) \tag{8}$$

where A_s is the backwater area, Mr is the resonance peak, ω_0 is the resonance frequency and $p \in [0\ \pi]$ is determined by the location of the discharge source and it is the phase of the wave expressed in radians. If downstream water level is expressed, the transfer function for upstream discharge source $p=\pi$ and for downstream $p=0$. In these cases Eq. (3) becomes the same equations as presented in [11]. For a discharge source L_s distance from upstream $p=L_s/L$ where L is the total length of the reach.

Applying the IR model to the case study

For each transfer function in Eq. (3) can be expressed in the form of Eq. (5). The variable p is different for each transfer function depending on the location of the discharge source and the measurement point. The values of p are summarized in Table 2.

Table 2: The values of the phase parameter (p) in different transfer functions of the CFR

Transfer f.	Value of p
G_{CC}	π
G_{AC}	0.679
G_{CA}	0.679
G_{AA}	π
G_{CF}	0
G_{AF}	0.322

The other variables in Eq. (5), namely the A_s, Mr and ω_0. are the same for each transfer function and are summarized in Table 3. The way of obtaining them is summarized in the following.

Table 3: The resonance characteristics of the CFR

Res. freq (rad/s)	Res. peak (s/m^2)	Backwater surface (m^2)

$4.53*10^{-4}$	0.0057	2199600

Obtaining the resonance characteristics of the reach and calculating the IR model

In order to apply the IR model to a canal reach the following characteristics are needed: the backwater area (A_s), the resonance frequency (ω_0,) and the resonance peak (Mr). The backwater area can be approximated as the surface area of the canal reach. Resonant canals are usually affected completely by backwater. The backwater surface can be approximated with the whole canal surface:

$$A_s = LB \tag{9}$$

where L is the length and B is the average width of the canal.

The resonance frequency and peak are more complicated to obtain. It can be obtained from field studies, for example from Auto Tune Variation experiments as described in [1]. If there is no experimental data the frequency plot of the canal can be approximated numerically and the value of the resonance peak and frequency can be read from the Bode plots.

The Bode plot of the CFR was obtained by using a distributed numerical model [3,4]. From the Bode plot (Figure 2) the characteristics of the reach can be read: the magnitude plot has a straight line in low frequencies: the canal reach behaves as an integrator. The reciprocal of the slope of this line is the A_s, the backwater area. In high frequencies resonance peaks can be seen. For controller development the first peak is the most important [8], and this is the parameter of the IR model: its frequency and its magnitude. This data is read from the plot and included to the model. The Bode plot of the resulting IR transfer function (G_{CF}) is shown in Figure 2 with dashed line. The transfer functions G_{CA} and G_{CF} are obtained in similar way.

Figure 3 shows the step response of the three transfer functions with the discharge at different locations. It can be seen that they have the same frequency but different phase.

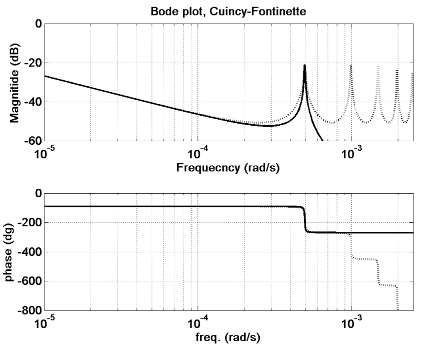	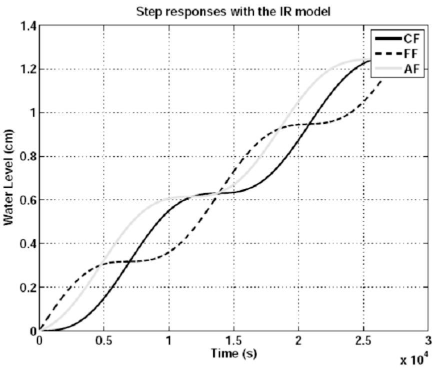
Figure 2: The IR model $G_{CF}(s)$, with balck of the Cuinchy-Fonitnettes reach compared to the Bode plot of a high order model with gray	Figure 3: Step response of the IR model, CF is from Cuinchy to Fontinettes, FF is Fontinettes to Fontinettes and AF is Aire to Fontinettes

Controller development

The controller development was carried out in the same way as detailed in [2]. The difference was the choice of the sampling time: for the resonance model a higher sampling (3600s) time is chosen.

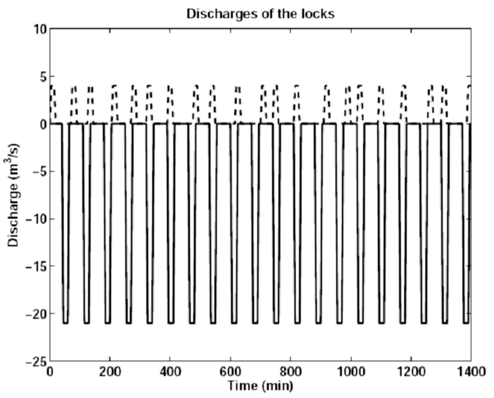

Figure 4: Discharge of the locks, continuous line is Fontinettes and dashed line is Cuinchy

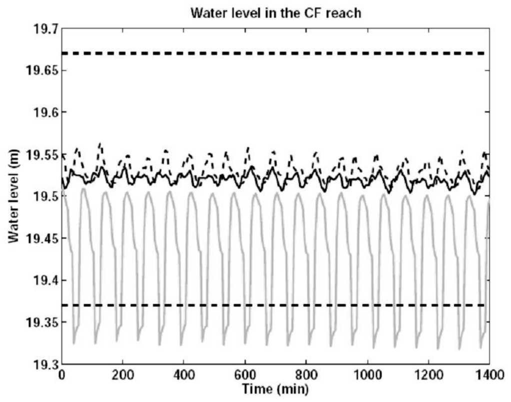

Figure 5: Water levels without control actions: with dashed line Cuinchy, continuous line Aire and gray line Fontinettes

RESULTS AND DISCUSSION

The system was tested using MPC based on the IR model for two different scenarios. In the first case the lock operations are unknown, they act as unknown disturbance. This corresponds to the actual operation of the CFR. The second scenario contemplates a future case, when the lock operations are possible to be predicted. In this case, the lock operations are known beforehand for the MPC controller and the controller can start acting before the lock operations occur.

The scenario includes 20 consecutive lock operations during one day. The discharges caused by these lock operations are shown in Figure 4. It can be seen that the magnitude of the maximum discharge is $4m^3/s$ for the lock of Cuinchy and $21m^3/s$ for the lock of Fontinettes. Without applying any control action these lock operations cause the water levels to be out of the navigation range: ±*15cm* (Figure 5). The water level at the lock of Fontinettes drops under the minimum affordable water level (*19.37m*).

Using the implemented controller with unknown disturbances the water levels are kept within the range of navigation. Figure 6 shows all the three water levels. They still fluctuate by the lock operation but they are kept within the range. Sometimes the level at Fontinettes is reaching the minimum allowed water level (with dashed straight line) but it stays within the range. The control actions are shown in Figure 7. The discharge at Cuinchy is kept at the possible maximum value while the discharge at Aire fluctuates. Note that the sampling time is one hour, and hence the gate movements are generated by the controller are separated with a long time interval. This is also advantageous in order to avoid wear and tear of the engines.

In case the lock operations are known the controller can treat them as known disturbances. The resulting water levels are shown in Figure 8. The water levels stay within the navigation range as expected before. The water level at Cuinchy is slightly higher than before, approaching more the upper limit. While the water levels at Fontinettes are further from the minimal limit compared to the case when the disturbances were unknown. The control actions are shown in Figure 9. Just as in the previous case the controller keeps the discharge at Cuinchy in the maximum and changes the discharge at Aire. The reason for this can be that the biggest changes occur at the downstream end, at Fontintettes. A change from Aire arrives earlier than from Cuinchy (upstream), therefore the controller manipulates more this intermediate discharge source.

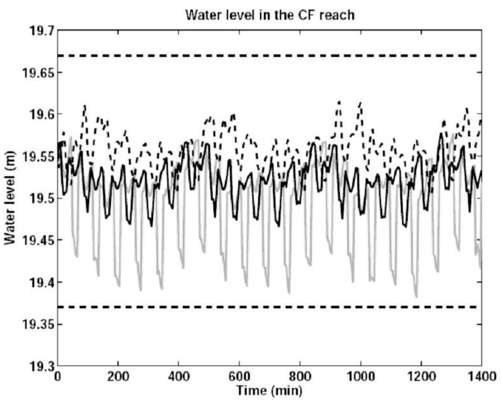

Figure 6: Controlled water levels: with dashed line Cuinchy, continuous line Aire and gray line Fontinettes

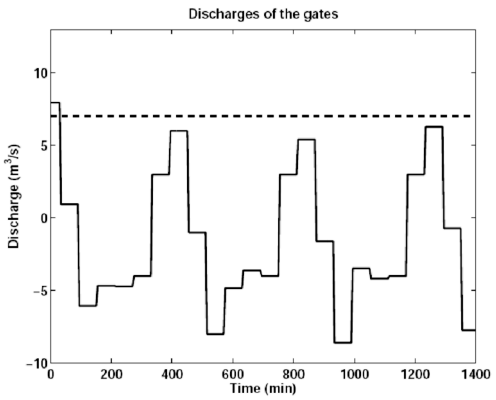

Figure 7: Discharge of the gates, continuous line is Aire and dashed line is Cuinchy

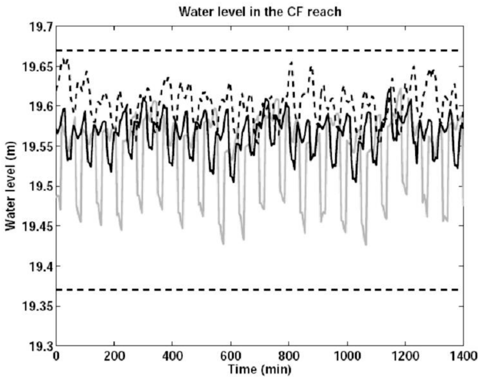

Figure 8: Controlled water levels: with dashed line Cuinchy, continuous line Aire and gray line Fontinettes

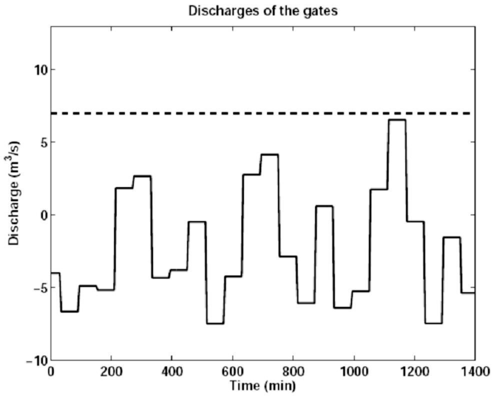

Figure 9: Discharge of the locks, continuous line is Aire and dashed line is Cuinchy

CONCLUSION

MPC controller based on a model including resonance was implemented to control the water level in a navigation reach. The water level is disturbed by the lock operations that generate big amplitude waves that are traveling several times back and forth in the reach. The goal to keep the water level within the range of navigation was achieved by the controller. This work belongs to the GEPET-Eau project that aims to the adaptive predictive management of navigation networks in the context of global change. This work contributes to the small scale modeling of a navigation reach. Further work can be to improve the modeling work, to study the influence of the resonance characteristics and the different operation conditions to the control. Finally the modeling and control work can be extended to the network of navigation reaches.

ACKNOWLEDGEMENT

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