MPC and PI control of the level of the inlet basin of a wastewater treatment plant

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Abstract: The basin level control system in an existing wastewater treatment plant is designed for two different operation modes: compliant level control for smooth pump flow, and stiff level control. Both a model-based predictive controller (MPC) and a standard PI controller are implemented, and tested both on a dynamic simulator and on the real plant. MPC appears to be the best controller for compliant level control, while the PI control is prefered for stiff level control. The simulator, the MPC and the PI controller tuning are based on a mathematical process model derived from a material balance of the wastewater in the inlet basin.

Keywords: Wastewater, basin, level, model-based predictive control (MPC), PI control.

INTRODUCTION

The aim if this article is to report results from a study where alternative controllers of the level of the inlet basin of the VEAS wastewater treatment plant (WWTP) at Slemmestad, Norway has been tested both on a dynamic simulator and on the real plant. VEAS is the largest WWTP in Norway, serving about 700,000 population equivalents (pe), treating in average about 3.5 m^3/s. The biological treatment at the WWTP will benefit from a smoother hydraulic load than at present. One approach to this end is improving the level control system of the inlet basin, aiming at smoother pump flow from the basin to the treatment processes (Bolmstedt, 2006; van Overloop et al., 2010).

The implementation of the simulator and the control system used in this study is in LabVIEW (National Instruments) with the MPC algorithm implemented in MATLAB code in LabVIEW's MATLAB Script node. The sampling time (time-step) of the various discrete-time algorithms of simulation, estimation, filtering, and control is 10 s.

The paper is organized in the following main sections: System description; Controller functions; Results; Conclusion; Abbreviations; Nomenclature; Acknowledgements; References.

SYSTEM DESCRIPTION

Geometrical design

Figure 1 depicts the principal geometrical design of the inlet part of the VEAS WWTP.

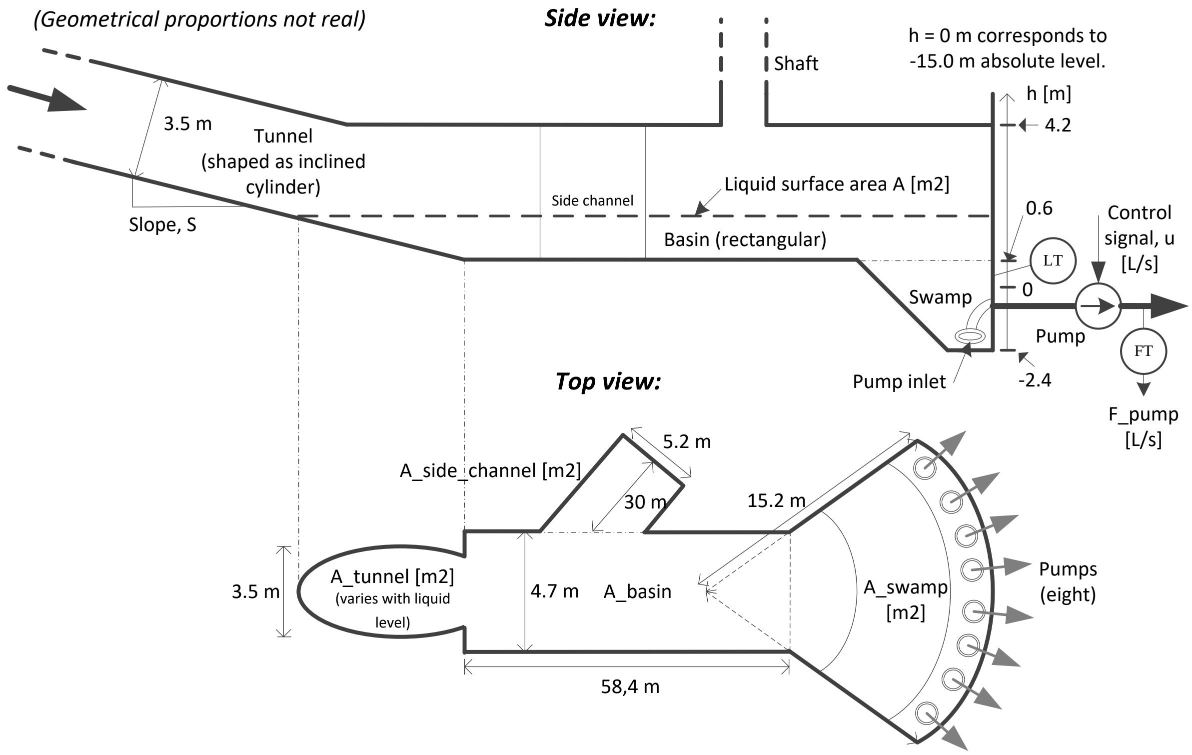


Figure 1. Principal design of inlet basin of VEAS WWTP.

Mathematical model of level of inlet basin

The basis of both the simulator and the model-based predictive controller is a dynamic model of the liquid level of the basin, Eq. 1. The model stems from material balance assuming the sewage is water.

$$dh(t)/dt = [F_{in}(t) - F_{out}(t)]/A[h(t)] \qquad (1)$$

In this study,

$$F_{out}(t) = F_{pump}(t) \qquad (2)$$

and

$$F_{in}(t) = F_{in\_meas}(t) + F_{in\_unmeas}(t) \qquad (3)$$

where F_{in_meas} are measured flows and F_{in_unmeas} are unmeasured flows.

The liquid surface area A in Eq. 1 is calculated from the assumed known geometry. The tunnel area is ellipsoidal and is continuously calculated by numerical integration.

The dynamics of the pump, cf. Figure 1, is taken into account by the level controllers. In the real plant, an apparent time-delay of approximately 120 s is observed between the pump control signal u and the resulting (measured) pump flow F_{pump}:

$$F_{pump}(t) = u(t - T_{delay\_pump}) \qquad (4)$$

For conservative controller tuning, the pump dynamics is represented by a time-delay of T_{delay_pump} = 120 s.

Piping and Instrumentation Diagram (P&I diagram)

Figure 2 shows a P&I diagram of the level control system.

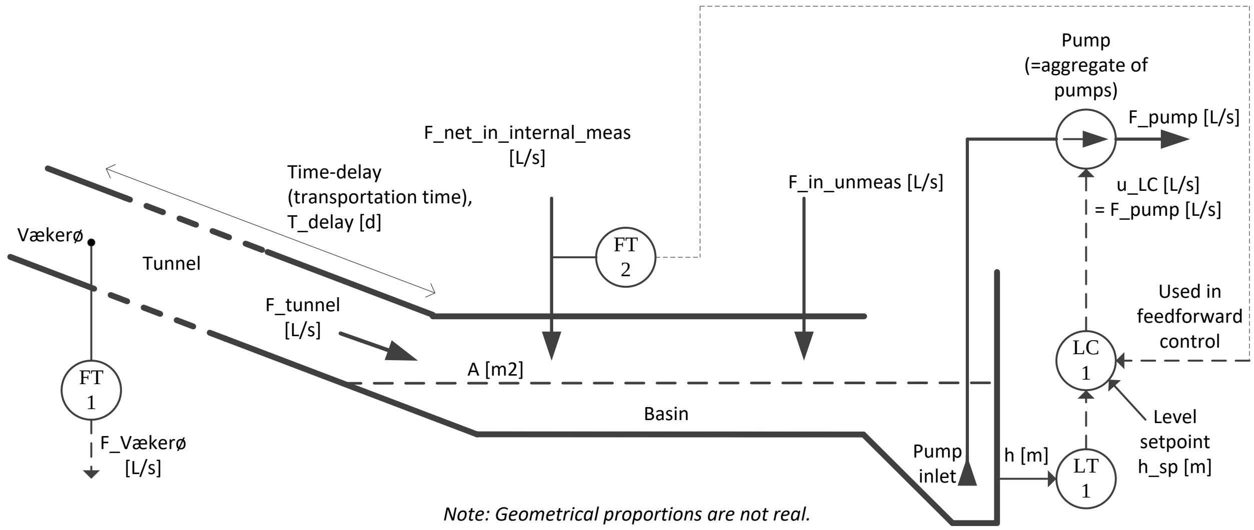


Figure 2. Piping and Instrumentation diagram (P&I D) of level control system of basin.

The flow at Vækerø, which is situated approximately 15 km upstreams the plant, constitutes the main inflow component to the plant, counting for 70-80% of the total tunnel inflow. The flow at Vækerø arrives at the plant with a transportation time (time-delay) of approximately 3.5 h, but largely flattened, so the transportation time is not well-defined. The flow at Vækerø is measured. This measurement is used in simulations. However, it is not used by the controllers in the real implementations in this study due to the uncertain information about its contribution to the actual inflow to the basin, as pointed out above. In the real implementations a Kalman Filter is used to estimate the net unmeasured inflow to the basin, and this estimate included en estimate of the flow at Vækerø.

Operation modes of the tunnel and basin and requirements to the level control system

The tunnel and basin can be operated in several different modes. The most important ones are described below, together with the pertinent requirements to the level control system:

1. ***Operation mode #1: Normally low load (tunnel flow) & Compliant level control***: The main aim of this mode is to obtain smooth pump flow. To this end, compliant level control is implemented: The level is allowed to vary between the soft limits of 1.8 m and 2.8 m, with 2.3 m as the nominal level setpoint.
2. ***Operation mode #2: Normally low load & Stiff level control***: The main aim of this mode is to have the level close to a relatively low setpoint to ensure that the pump soaks up solid downfall from the wastewater accumulated in the basin during Operation mode no. 1. The duration of this operation mode is relatively short, approximately two hours, each second day. In this operation mode, the variations of the pump flow will, inevitably, be relatively large as they are almost the same as the variations of the net inflow to the basin.
3. ***Operation mode #3: Normally high load***: This mode is used during high preciptiation. Additional outlet pumps ("rain weather pumps") from the basin are activated. The basin level

is controlled manually by the operators by their manipulation of the maximum allowable pump flow.

4. ***Operation mode #4: Tunnel flushing***: At the start of this mode, the pumps at the beginning of the tunnel (not shown in Figure 2) reduce the flow, and then they increase the flow to a very large value. When the flushed wastewater arrives the basin, the flow through the basin pumps are limited by the operators to values which are considerably smaller than the tunnel flow, and consequently, the level of the basin typically reaches a very high value. After several hours the level is again back to normal values, and typically, Operation mode #1 becomes active.

In this study, only Operation modes #1 and #2 are considered. (Operation modes #3 and #4 will be focused in a future study.)

CONTROLLERS

Two different controllers are used in this study, namely (a) MPC and (b) PI control with the option of feedforward from measured disturbance (measured washing water).

MPC

A nonlinear MPC is used in this study (Grüne and Pannek, 2011). The optimization problem of the MPC is

$$\min_{u_{LC}} \int_{t_0}^{t_0+Tp} \left\{ C_1 e(t)^2 + C_2 \left[\frac{d(u_{LC})}{dt} \right]^2 \right\} dt \qquad (5)$$

where the integral is the objective function to be minimized. The optimization variable is the pump flow (control variable). $e = h_{sp} - h$ is control error. $d(u_{LC})/dt = d(F\_pump)/dt$ is rate of change of pump flow (control variable). C_1 and C_2 are cost coefficients. T_p is the prediction horizon. t_0 is the present point of time. The MPC finds the sequence of sampled future pump flow values (u_{LC}) that gives the optimal balance or compromise between small control error and small rate of change of pump flow. To save the computional demand, control signal locking is used, i.e. the number of allowable values during the prediction horizion is set to N_p. The MPC predicts how the pump flow should be adjusted in advance to compensate for the future tunnel flow as known from the upstream flow measurement at Vækerø.

The MPC uses the measurement of washwater flow, $F_{washwater}$. To compensate for the uncertainty of the time-advance of the measurement (as discussed earlier in the paper), the measurement is passed through a time-constant lowpass filter of time-constant $T_{filt\_washwater}$ before being used in the MPC.

The MPC uses a continuous estimate of the total of the unmeasured flows by a Kalman Filter, see below.

The MPC takes into account level constraints and control variable (pump flow) constraints. MATLAB's `fmincon` function is used as optimization function.

Kalman Filter

The estimate of the total of the unmeasured flows is calculated with an Extended Kalman Filter (EKF) algorithm (Simon, 2006) where the state variables (two) are level and total unmeasured flow (the latter is an augmented state variable), the measurement that corrects (updates) the state estimate is the level measurement, and the model used for the prediction is the process model, Eqs. (1) - (4).

PI controller

A standard PI controller (Seborg et al., 2004) used:

$$u(t) = K_c \cdot e(t) + (K_c/T_i) \cdot \int_0^t e(\tau)\, d\tau \ + u_f(t) \qquad (6)$$

where u_f is an additive feedforward term, derived below. The PI controller is tuned with the Skogestad method (Skogestad, 2003) for "integrator plus time-delay" process dynamics, but with a modification where the integral time, T_i, is reduced to obtain faster disturbance compensation (Haugen and Lie, 2013). The process model assumed in the PI tuning is on the form of the following differential equation:

$$dy(t)/dt = K_i \cdot u(t-T_{delay}) \qquad (7)$$

which can be written on the alternative form of an integral equation as follows:

$$y(t) = K_i \cdot \int_0^t u\left(\tau - T_{\text{delay}}\right) d\tau \qquad (8)$$

The process model, Eqs. (1) - (4), is on the form of Eq. (7) with y = h, u = F_{pump}, and

$$K_i = 1/A \qquad (9)$$

The Skogestad PI settings for the process model Eq. (5) or (6) are:

$$K_c = 1/[K_i \cdot (T_c + T_{delay})] \qquad (10)$$

$$T_i = 2(T_c + T_{delay}) \qquad (11)$$

where: T_{delay} is the process time-delay, and T_c is the user-specified time-constant of the closed loop system (control system). In the present study, $T\_{delay} = T_{delay\_pump}$.

In general, the PI controller can be tuned for satisfactory performance using T_c as follows: By increasing T_c, the control systems typically becomes more sluggish: The control signal becomes smoother, and the control error becomes larger. On the other side, by decreasing the closed loop time-constant, the control systems typically becomes more aggressive (faster): The control signal varies more abruptly, and the control error becomes smaller.

Feedforward control

The feedforward term, u_f, in Eq. (4) is derived from the process model Eqs. (1) - (4) as follows. By inserting Eqs. (2) - (4) into Eq. (1), the latter can be written as

$$dh(t)/dt = [F_{in\_meas}(t) + F_{in\_unmeas}(t) - u(t-T_{delay\_pump})]/A[h(t)] \qquad (12)$$

Solving for the control variable, u, and substituting the level, h, by its setpoint, h_{sp}, yields the feedforward controller:

$$u_f(t) = F_{in\_meas}(t+T_{delay\_pump}) + F_{in\_unmeas}(t+T_{delay\_pump}) - dh(t+T_{delay\_pump})/dt \cdot A[h(t+T_{delay\_pump})] \qquad (13)$$

Assuming constant level setpoint and disregarding unmeased inflows, yields the following resulting feedforward controller:

$$u_f(t) = F_{in\_meas}(t+T_{delay\_pump}) \qquad (14)$$

The largely dominant component of F_{in_meas} is the wash-water return flow, $F_{washwater}$, from the treatment processes into the basin. The washwater flow is actually measured time $T_{washwater}$ in advance, before the flow actually enters the basin. Hence,

$$F_{in\_meas}(t) \approx F_{washwater}(t) = F_{washwater\_meas}(t\text{-}T_{delay\_washwater}) \quad (15)$$

$T_{delay\_washwater}$ is, to some extent, poorly known and also varying with operating conditions, but it is typically in the range 5 - 7 mins. Combining Eqs. (14) and (15) yields the resulting feedforward controller:

$$u_f(t) = F_{in\_meas}(t - [T_{delay\_washwater} - T_{delay\_pump}]) = F_{washwater}(t - [T_{delay\_washwater} - T_{delay\_pump}]) \quad (16)$$

RESULTS

Tests on the simulated plant

For both Operation modes #1 and #2, basin level control with MPC and with PI control with and without feedforward control from washwater flow has been tested on the dynamic simulator based on the process model. To make the simulation as realistic as possible, the simulations has been driven by historical data from the real plant. The simulations has been succesful. However, to limit the size of this article, and because simulation results does not add substantial information comparing to results from real tests, detailed results of the simulations are not included in this paper. Results from the real implementation are presented in the subsequent section.

Tests on the real plant

After successful simulations, the various controllers were tested on the real plant. The same parameter settings of the controller, the Kalman Filter, etc. used on the simulator, were used as initial settings in the real test. Only for a few parameters, parameter adjustments were necessary. However, it turned out that although feedforward from measured washwater flow improved the stiff level control (with PI controller) substantially, improvements were hard to observe in the real test. This is certainly due to modelling errors, but this issue was not analyzed in detail, but may be addressed in a future study.

The various tests are presented below. More tests were run than those presented in the following. Although the tests presented are representative, it is recommended that even more test are run before decisions about controllers are taken.

At present, the plant is operated continuously with a PI controller for basin level control. Responses with the present controller are not included in this paper because the controller is not tuned for operation in neither Operation mode #1 nor Operation mode #2 as defined above, so a comparison is of limited value.

Operation mode #1: Normally low load (tunnel flow) & Compliant level control

<u>MPC</u>

MPC settings: C_1 = 1 and C_2 = 64 (emphasizing smooth control). T_p = 30 min. N_p = 3. T_filt_washwater = 300 s. Kalman Filter settings: Process disturbance covariance: Diag(0.1, $1.0\cdot10^6$). Measurement noise covariance: 0.1.

Figure 3 shows results with MPC in Operation mode #1. Observations: The level is within the limits. The pump flow varies between 2400 and 3200 L/s which is a maximum variation of 800 L/s.

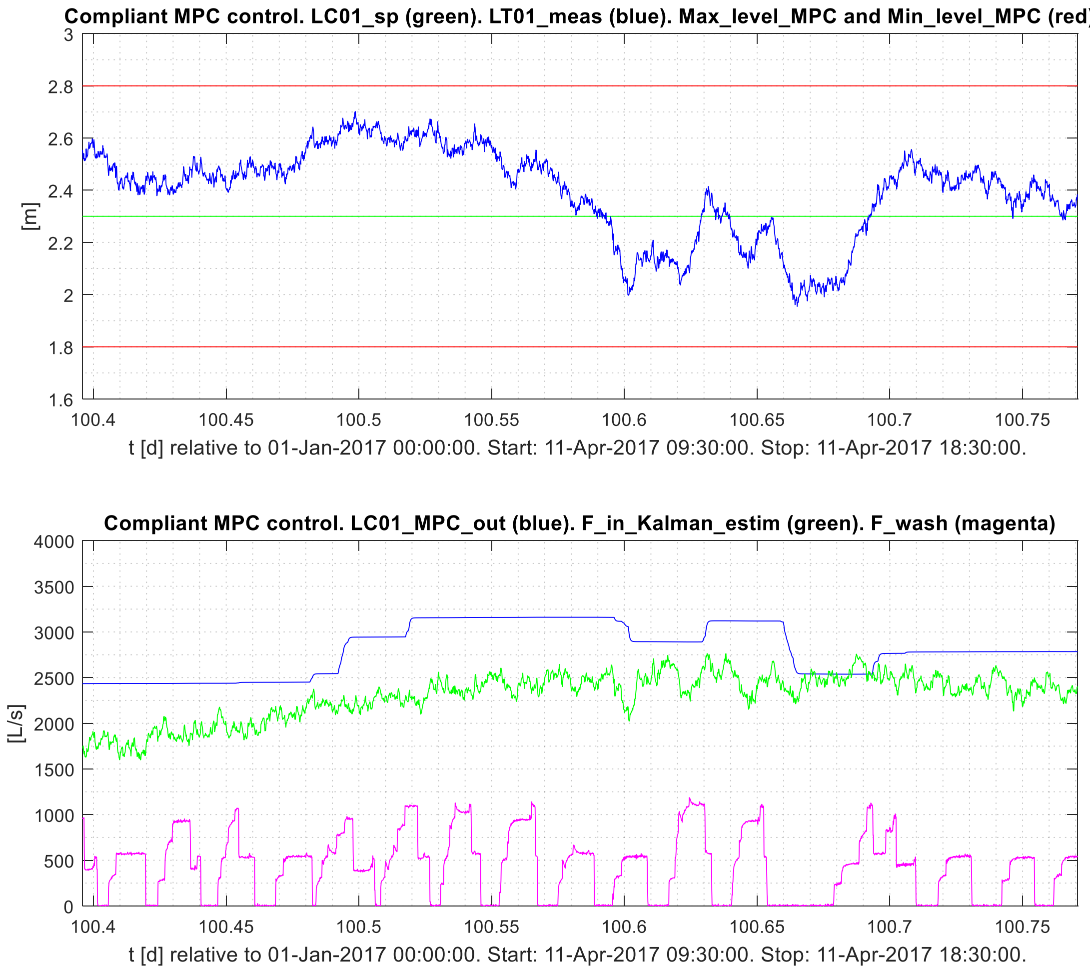


Figure 3: Results with MPC in Operation mode #1 (compliant level control). Time range: 9 h.

PI controller

PI controller settings: T_c = 2000 s. Basin surface area at operating point: A = 2000 m2, corresponding approximately to level of 1.8 m. Resulting PI settings: K_c = 944 and T_i = 4280 s.

Figure 4 shows results with PI control in Operation mode #1. Observations: The minimum level is approximately 1.7 m which is slightly less than the lower limit of 1.8 m. The pump flow varies between 1500 and 3250 L/s which is a maximum variation of 1750 L/s.

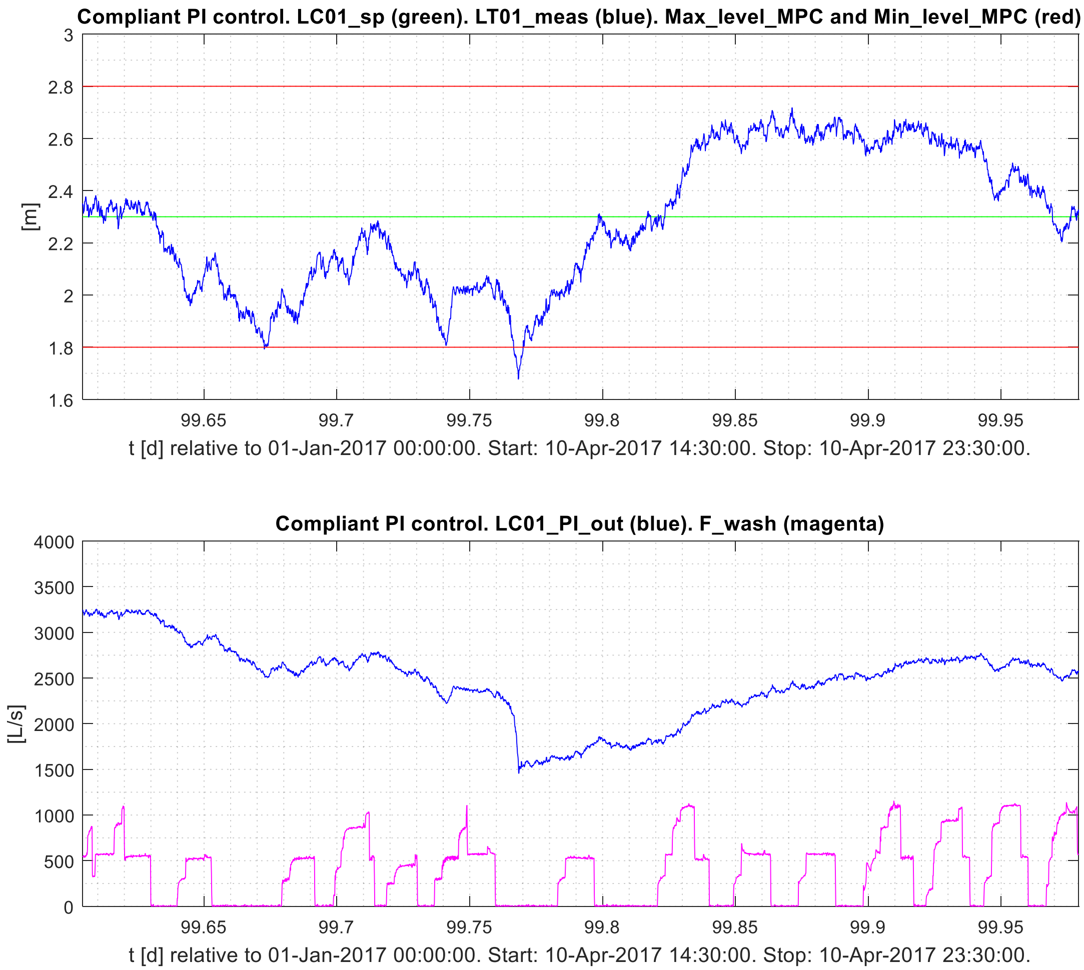


Figure 4: Results with PI control in Operation mode #1 (compliant level control). Time range: 9 h.

Operation mode #2: Normally low load & Stiff level control

<u>MPC</u>

MPC settings: $C_1 = 1$ and $C_2 = 0.02$ (emphasizing small control error). $T_p = 30$ min. $N_p = 3$. T_filt_washwater = 300 s. Kalman Filter settings: As above.

Figure 5 shows results with MPC in Operation mode #2. Observations: The control system seems to have poor stability, and the minimum level is approximately 1.4 m which is regarded as too low.

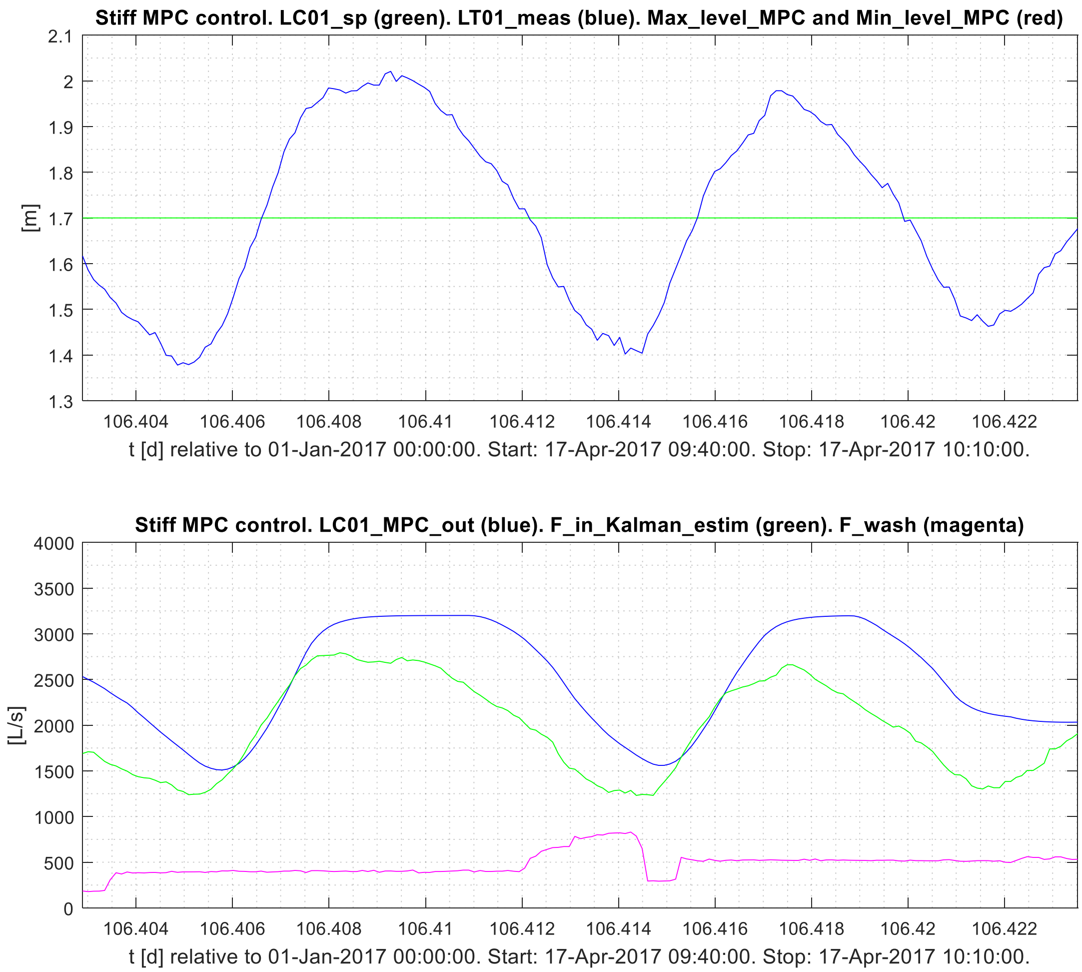
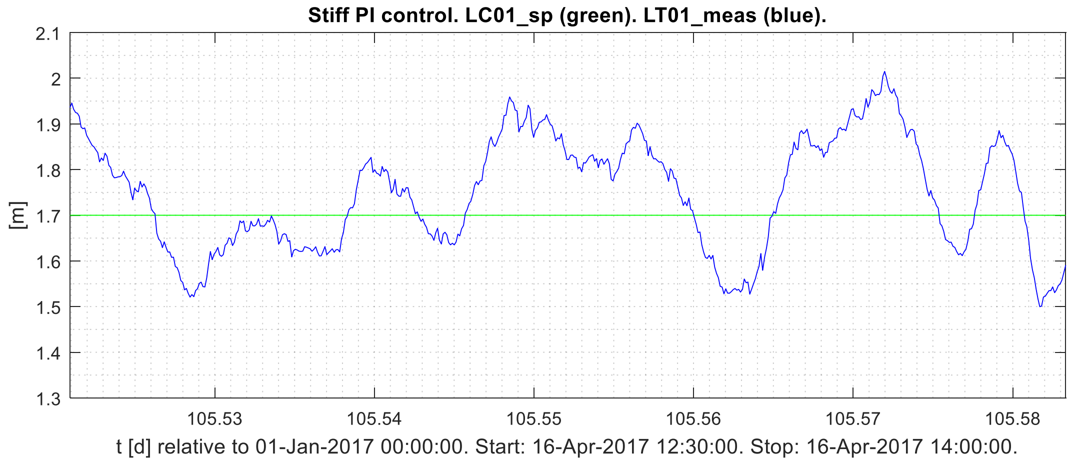


Figure 5: Results with MPC in Operation mode #2 (stiff level control). Time range: 1.5 h.

PI controller

PI controller settings: Tc = 500 s. Basin surface area at operating point: A = 1700 m2, corresponding approximately to level of 1.6 m. Resulting PI settings: K_c = 2744 and T_i = 1240 s.

Figure 6 shows results with PI control in Operation mode #2. Observations: The minimum level is approximately 1.5 m which is acceptable. There is no sign of instability in the control system.



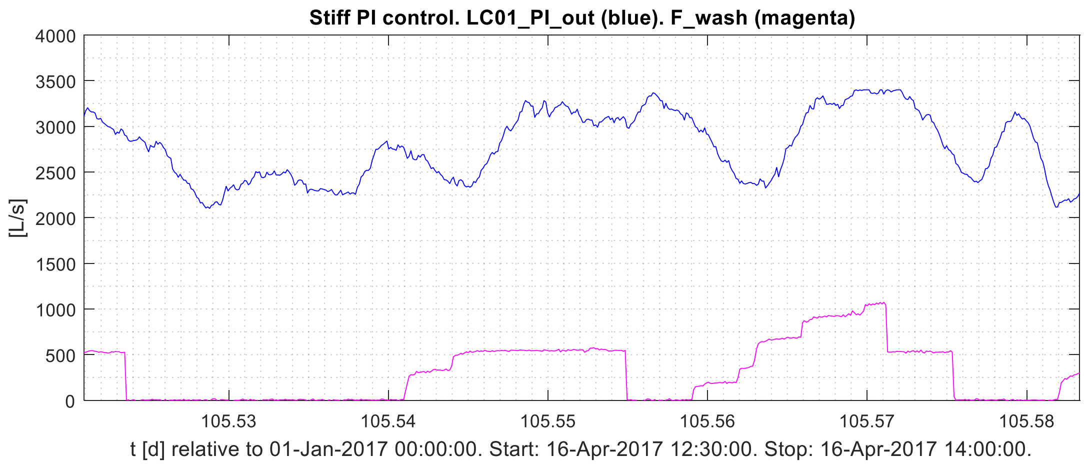


Figure 6: Results with PI control in Operation mode #2 (stiff level control). Time range: 1.5 h.

CONCLUSION

For Operation mode #1 (compliant level control), MPC appears better than PI control becauses it (almost) ensures that the level stays between level limits while also providing smoother pump flow.

For Operation mode #2 (stiff level control), PI control appears better than PI control because it gives better control system stability, and prevents the level from becoming too low. However, if the model errors are identified and corrected, the MPC can be expected to outperform the PI controller, as it does in simulations.

One important lesson to learn from this study is that by using a sufficiently accurate dynamic simulator for tuning and testing control systems,

- controller functionality can be verified *before* practical application,
- controller parameters can be tuned on the simulator *before* practical application,

with benefits regarding time use, labour, economy, process regularity, and safety.

ABBREVIATIONS

EKF: Extended Kalman Filter.

FT: Flow Transmitter (sensor).

LC: Level Controller.

LT: Level Transmitter (sensor).

MPC: Model-based predictive control

PID: Proportional + Integral + Derivative

NOMENCLATURE

Parameters and variables in alphabetical order:

A [m^2]: Surface area of liquid.

C_1 and C_2 are cost coefficients of MPC.

e (t): Control error, i.e. level setpoint minus level measurement, $e = h_{sp} - h$.

F_{in} [m^3/s] or [L/s]: Total inflow to the basin.

F_{in_meas} [m^3/s] or [L/s]: Total measured inflows to the basin.

F_{in_unmeas} [m^3/s] or [L/s]: Total unmeasured inflows to the basin.

F_{out} [m^3/s] or [L/s]: Total outflow of the basin.

F_{pump} [m^3/s] or [L/s]: Total basin pump flow.

h [m]: Water level of basin.

h_{sp} [m]: Setpoint of water level of basin.

K_c [(L/s)/m]: Gain of PI controller.

K_i: Process integral gain.

N_p [1]: Number of allowable control signal values during the prediction horizion in MPC.

T_p [s] or [min]: Prediction horizon of MPC.

t_0 [s]: Present point of time of MPC.

T_c [s]: Closed-loop time-constant in the Skogestad PI tuning method.

T_{delay_pump} [s]: Approximate time-delay of basin pump.

T_i [s]: Integral time of PI controller.

T_{delay_pump} [s]: Time-delay of pump.

$T_{filt\_washwater}$ [s]: Time-constant of lowpass filter of washwater flow measurement.

u [L/s]: Pump flow demanded by the level controller.

u_f [L/s]: Additive feedforward term in the PI controller.

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