A Simulation Study on the Optimal Control of Lock and Dam Gate Openings by the Self-Tuning Controller

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INTRODUCTION

In industries, there has been considerable interest during the past decade in self-tuning (or adaptive) control systems which automatically adjust controller parameters on-line in response to changes in the process or the environment. Self-tuning has considerable potential for process control problems since it provides a systematic, flexible approach for dealing with uncertainties, nonlinearities, and time-varying parameters. Adaptive stochastic controllers have become practical due to the readily available inexpensive computer systems (Cameron and Seborg, 1983).

Control problems in water resources engineering tend to be characterized by nonlinearities, time delays and time-varying parameters; they also tend to change unpredictably. Hence, this study aims to demonstrate the applicability of an adaptive stochastic controller, the self-tuning controller (STC) of Clarke and Gawthrop (1975), for the real-time control problems in water resources engineering. We achieve this objective by simulating the control of the lock and dam gate openings to maintain a certain water level upstream of the gates. This control aims to prevent sea water from invading the reservoir (above the lock and dam) where abstractions for domestic, agricultural and industrial water supplies are located.

This control problem has been solved by Duong, et al. (1978) (for navigation purpose) using cautious control law (one type of self-tuning regulator (Astrom and Wittenmark, 1973)) reported by Wieslander and Wittenmark (1971). The difficulties associated with this control law (such as "turn off" and "escape" phenomena) make it less useful (Astrom, 1980). Also the required water level is not a direct function of the control law. Though STC has already been applied to the optimal control of groundwater abstraction in the simulation study discussed by Ganendra (1980), as far as we know, its availability to other control problems in water resources engineering has not yet been investigated.

Existing control of the lock and dam gate openings is to check, at regular time intervals, the upstream and downstream water levels, the present gate openings, and the river discharge from a nearby upstream station and open the gates according to the design rules. This type of control is not very efficient in treating the random nature of the inflow. Also, the design rules are fixed, and the gate openings may not be optimal because of the stochastic nature of the operating conditions. Moreover, the gate openings are determined without considering whether the response of the water level water level will meet the required one. Therefore, being able to derive an optimal control law appropriate to the present operating conditions and satisfying the specified upstream water level would provide a control of the gate opening better than the existing control strategy.

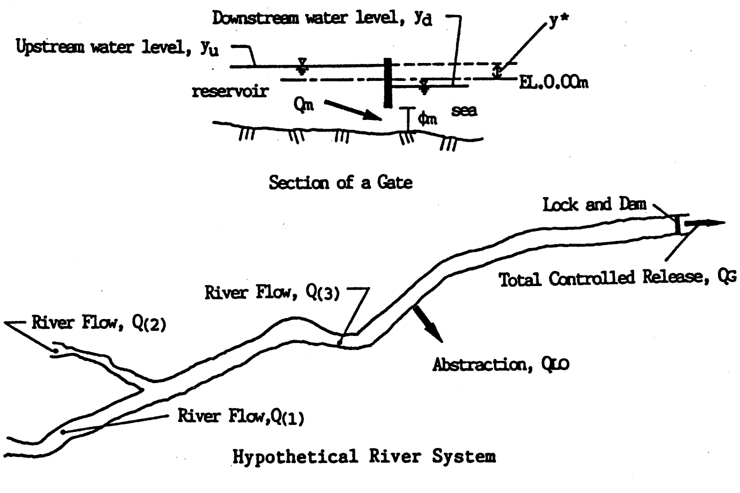

Fig.1 Lock and dam gate openings control problem.

SELF-TUNING CONTROLLER AND PROBLEM FORMULATION

We consider the system shown in Fig.1, which is described by the following equation

$$A(q^{-1})y_u(t) = B'(q^{-1})Q_C(t-k)+C'(q^{-1})Q_{(3)}(t-k)+D'(q^{-1})Q_{L0}(t-k)+E(q^{-1})v(t) \quad (1)$$

where $y_u(t)$ is the system output (upstream water level), $Q_C(t)$ is the system input or control variable (total gate discharge), $Q_{(3)}(t)$ (inflow) and $Q_{L0}(t)$ (abstraction) are uncontrollable (but observable) inputs, $v(t)$ is the uncorrelated zero-mean random sequence, and t and k denote the sampling instant and the pure time delay between the input and output respectively. The polynomials $A(q^{-1})$, $B'(q^{-1})$, $C'(q^{-1})$, $D'(q^{-1})$ and $E(q^{-1})$ are expressed in terms of the backward shift operator, q^{-1}

$$A(q^{-1})=1+a_1q^{-1}+\cdots+a_nq^{-n};\ B'(q^{-1})=b_0+b_1q^{-1}+\cdots+b_nq^{-n};\ C'(q^{-1})=c_0+c_1q^{-1}$$

$$+\cdots c_nq^{-n};\ D'(q^{-1})=d_0+d_1q^{-1}+\cdots+d_nq^{-n};\ \text{and } E(q^{-1})=1+e_1q^{-1}+\cdots+e_nq^{-n} \quad (2)$$

where n is the order of the system.

Using the identity

$$G=(E-AF)q^k \quad (3)$$

where F and G are polynomials of order $k-1$ and $n-1$ respectively.

$$F(q^{-1})=1+f_1q^{-1}+\cdots+e_{k-1}q^{1-k}\ ;\ \text{and}\ \ G(q^{-1})=g_0+f_1q^{-1}+\cdots+e_{n-1}q^{1-n} \quad (4)$$

the optimal k-step predictor for the system equation (1) is given by eq.5 which is derived following the minimum square error predictor of Astrom (1970).

$$\hat{y}_u(t+k\,|\,t)=\frac{G}{E}y_u(t)+\frac{B'F}{E}Q_C(t)+\frac{C'F}{E}Q_{(3)}(t)+\frac{D'F}{E}Q_{L0}(t) \quad (5)$$

The prediction error is given by

$$\varepsilon(t+k)=Fv(t+k) \quad (6)$$

The objective of STC is to predict the input $Q_C(t)$ such that the system output $y_u(t+k)$ is equal to a target value or 'set point'. Defining a generalized output function ψ such that

$$\psi(t+k)=y_u(t+k)-y^*(t+k)+\lambda\{Q_C(t)-Q_C(t-1)\} \quad (7)$$

The STC is designed to minimize the variance ψ. Here $y^*(t+k)$ is the set point which is the required upstream water level, and the factor λ is used to stabilize the controller by penalizing the control effort, defined as the change in the control variable from one time step to the next (Ganendra, 1980).

In order to predict $\psi(t+k)$, $y_u(t+k)$, unknown at time t, must be replaced by $\hat{y}_u(t+k\,|\,t)$ so that

$$\hat{\psi}(t+k\,|\,t)=\hat{y}_u(t+k\,|\,t)-y^*(t-k)+\lambda\{Q_C(t)-Q_C(t-1)\} \quad (8)$$

with output prediction error equal to $\varepsilon(t+k)$ (eq.6), i.e.

$$\psi(t+k)=\hat{\psi}(t+k\,|\,t)+\varepsilon(t+k) \quad (9)$$

In order to implement the self-tuning scheme, eq.5 is substituted into eq.8 to obtain

$$E\hat{\psi}(t+k\,|\,t)=Gy_u(t)+BQ_C(t)+CQ_{(3)}(t)+DQ_{L0}(t)-Ey^*(t+k) \quad (10)$$

where $B=B'F+\lambda E\{1-q^{-1}\}$, $C=C'F$ and $D=D'F$.

If $\hat{\psi}(t+k\,|\,t)$ is forced to zero at every time step, then rearrangement of eq.10 yields the feedback control law that minimizes the variance of $\psi(t)$

$$Q_G(t)=-\frac{1}{B}\{Gy_u(t)+CQ_{(3)}(t)+DQ_{LO}(t)-Ey^*(t+k)\} \qquad (11)$$

Unlike the cautious control law used by Duong, et al.(1978), the self-tuning controller (eq.11) considers a variable set-point.

In order to implement the feedback control law, the coefficients of the polynomials B, C, D, E and G can be estimated by Kalman filter for the process

$$\theta(t+1)=\theta(t) \qquad (12)$$

$$\psi(t)=H(t)\theta(t)+\varepsilon(t) \qquad (13)$$

where

$$\theta^T(t)=\{b_0,\cdots,b_{j-1},c_0,\cdots,c_{l-1},d_0,\cdots,d_{m-1},-e_0,\cdots,-e_{p-1},g_0,\cdots,g_{s-1}\};$$ and $$H(t)=\{Q_G(t),\cdots,Q_G(t-j+1),Q_{(3)}(t),\cdots,Q_{(3)}(t-l+1),Q_{LO}(t),\cdots,Q_{LO}(t-m+1),y^*(t+k),\cdots,y^*(t+k-p-1),y_u(t),\cdots,y_u(t-s-1)\} \qquad (14)$$

The parameters j, l, m, p and s are the number of terms in the respective polynomials B, C, D, E and G. At every time step t, $\psi(t)$ is computed as

$$\psi(t)=y_u(t)-y^*(t)+\lambda\{Q_G(t-k)-Q_G(t-k-1)\} \qquad (15)$$

which is considered as the measured value of ψ at time t.

Fig.2 shows the flowchart of the STC algorithm for the optimal control of lock and dam gate openings. In this flowchart, Q_{Lim} serves as the maximum inflow which can be controlled by the gates. When inflow is greater than Q_{Lim}, the gates are fully opened to ensure the safety of the lock and dam structure; Q_G is the uncontrolled discharge under the gates. The imposition of this constraint would illustrate some nice properties of the use of STC to this control problem. Also, the present setting of this constraint in the flowchart provides a more stable parameter estimates after recontrolling the gate openings during flood recession.

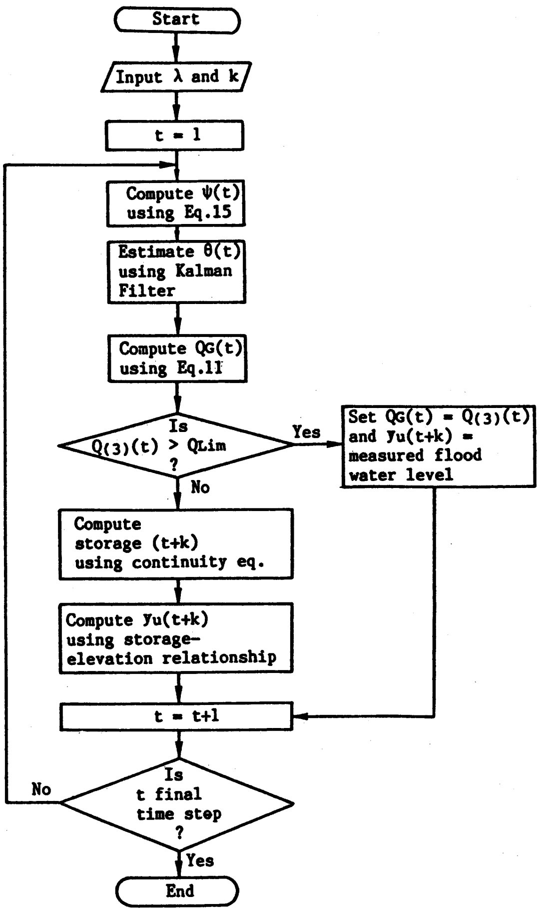

Fig.2 Flowchart of the STC algorithm.

SIMULATION RESULTS AND DISCUSSION

We consider the control law for the system shown in Fig.1 to be

$$Q_G(t)=-\frac{1}{b_0}\{g_0y_u(t)+b_1Q_G(t-1)+c_0Q_{(3)}(t)+c_1Q_{(3)}(t-1)+c_2Q_{(3)}(t-2)+d_0Q_{LO}(t)+d_1Q_{LO}(t-1)-y^*(t+k)-e_1y^*(t+k-1)\} \qquad (16)$$

In implementing the STC algorithm, $k = 1$ and $\lambda = 0.00001$.

Fig.3 shows the behaviour of the estimates of the controller parameters, starting from time-step 42. The variations of the parameter estimates are typical of a self-tuning algorithm.

For this simulation study, we select the period with high inflows since it is the most critical stage in the control of gate openings. Fig.4a shows the inflow time series with two flood periods. With this data, the performance of the STC algorithm is easily evaluated especially when the control law (eq.16) is reapplied during flood recession.

In order to meet y^*, the optimal Q_C should be equal to the $Q_{(3)}$. Fig.4b shows a fluctuating time series plot for Q_C (full line) obtained using the existing control strategy and a smooth one by the STC algorithm (broken line). The gate discharges calculated using the control law are practically equal to the inflows, except at the initial stage of the reapplication of the control law during flood recession (where undesirable gate discharges are obtained). In contrast, the gate discharges obtained using the existing control strategy are either higher or lower than the inflows.

The plot of y_u is reflected by that of Q_C. In Fig.4c, observe that $y^* = 1.45$m is practically met between time-steps 68 and 358 and between time-steps 434 and 751 but not after time-step 769. On the other hand, y_u computed by the existing control strategy is either higher or lower than the target level. This indicates that the response of the resulting y_u with respect to y^* is being disregarded in the calculation of Q_C by the existing control strategy.

One of the interesting features of STC algorithm is that it can prevent the unnecessary depletion of the reservoir (shown by the existing control strategy) after the passage of the flood crest. This is demonstrated by the behaviour of y_u, which shows that the gate openings can be recontrolled as early as time-step 412. However, the channel hydraulics of the actual system must be verified if, in reality, we were to follow this control suggested by the STC algorithm.

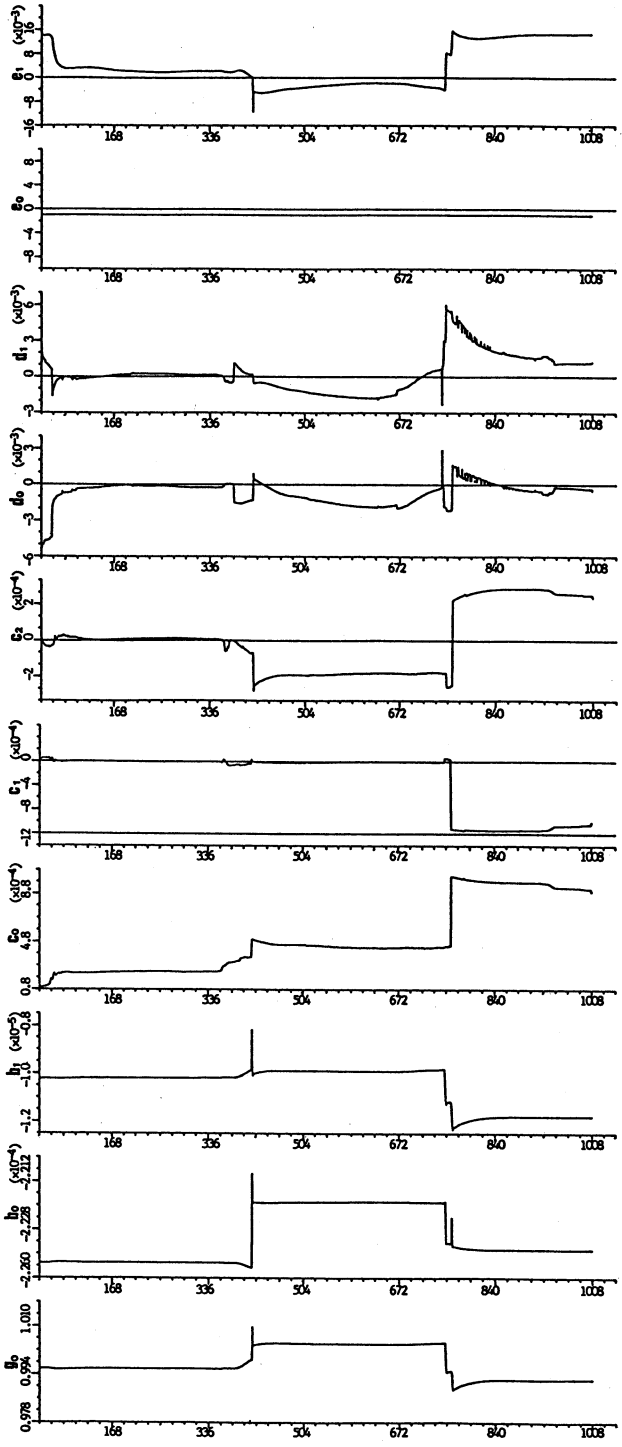

Fig.3 Variations of the controller parameter estimates.

Fig.4d shows the time series plot of the generalized output function ψ, expressing explicitly the behaviour of the difference between y_u and y^* and implicitly the behaviour of the innovation sequence of the Kalman filter algorithm. It shows that the y_u is within $\pm$ 1cm of y^* in the intervals between time-steps 68 and 358 and between time-steps 434 and 751. High values of ψ after time-step 769 are caused by the failure of y_u to converge to y^*. Extremely high and low values during the flood crest result from setting y_u equal to the actual flood water level after the inflow has exceeded Q_{Lim}, and gates are all fully opened. In this period, the estimation process by Kalman filter continues, yielding unstable parameter estimates as shown in Fig.3. This instability is due to the large innovations caused by the large values of ψ. Extreme values are also obtained after the inflow drops below Q_{Lim}. These are due to abrupt changes in the controller parameter structures (as shown in Fig.3) when the control law is reapplied during flood recession. Extreme values of the parameter estimates are obtained at the initial stage of the reapplication, causing the undesirable gate discharges shown in Fig.4b. During this period of undesirable gate discharges, one should use the existing design rules until the controller parameter estimates have practically converged (Duong, 1978). Notice in Fig.3 that, during the recession of the first flood, the parameter estimates have converged after very few time-steps, causing a stable and converging behaviour of ψ and y_u.

However, although Q_G is close to $Q_{(3)}$, y_u fails to converge to y^* after the

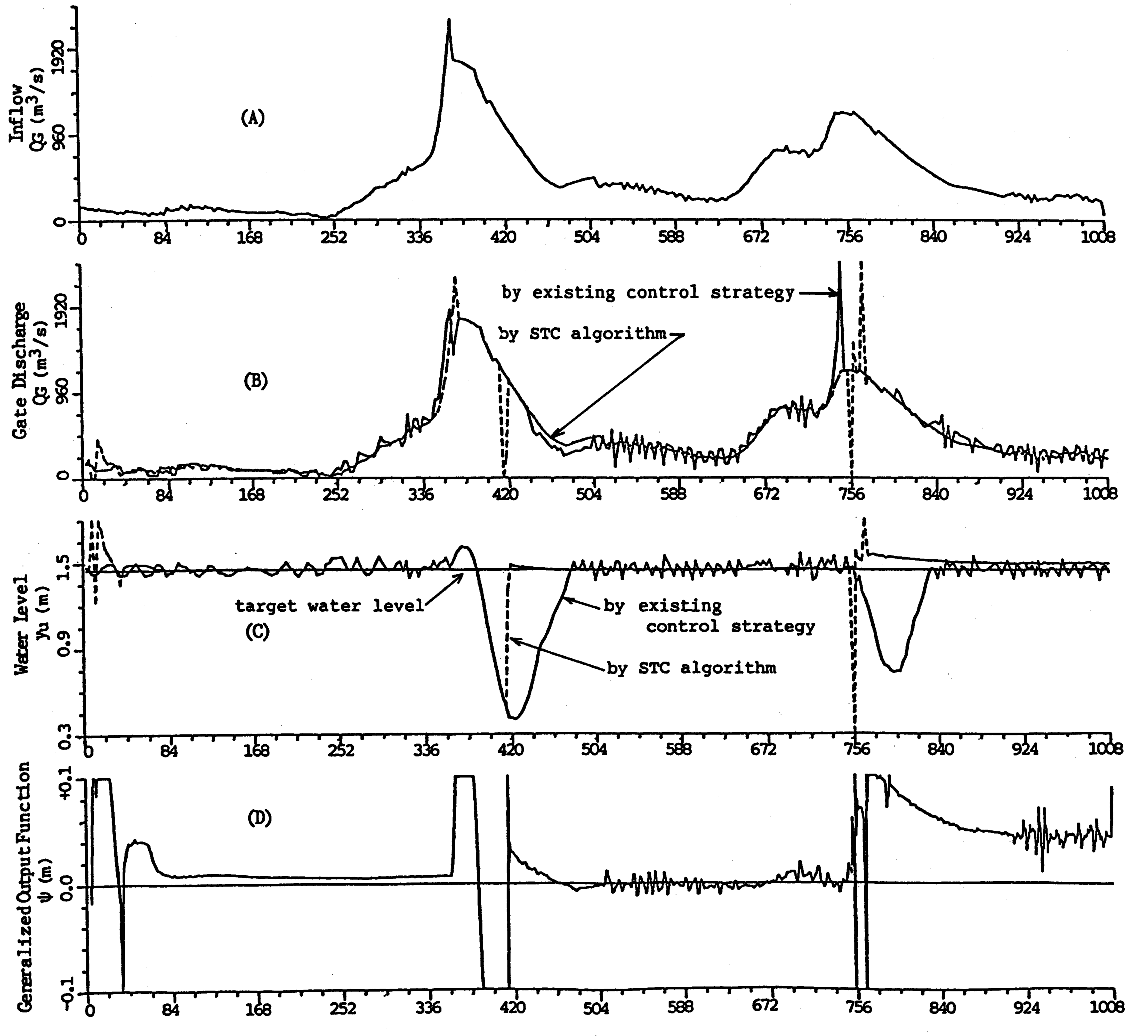

Fig.4 Time series plots of A) inflow $Q_{(3)}$, B) total gate discharge Q_G, C) water level y_u, and D) generalized output function ψ.

reapplication of the control law during the recession of the second flood as has been mentioned above. At this instant, the error covariance matrix P of the Kalman filter has become too small, disallowing the continual monitoring of the innovation to detect variations in the parameters. This suggests that the parameter estimates indicated in Fig.3 after time-step 769 are converging at a very slow pace, creating large innovations which P has failed to correct. This problem needs further research to improve the performance of STC to this control problem. Although there is an algorithm for recursive least-square estimation which incorporates a "forgetting factor" (Ganendra, 1980) if the parameters are time-varying, we are contemplating on the use of the adaptive Kalman filter (Ueda, et al., 1984) to solve this problem. This adaptive Kalman filter detects on-line the abrupt changes in the system, estimates their magnitudes and automatically compensates not only the error covariance matrix but also the parameter estimates according to the magnitudes of these abrupt changes.

The gate discharge $Q_G(t)$ has to be aggregated; for a value of $Q_m(t)$, the discharge under gate m, a corresponding value $\phi_m(t)$, the gate opening height, is calculated depending on the existing hydraulic condition of the system.

In this study, a value of λ greater than λ=0.00001 could lead to divergence. Notice in the control law (eq.16) that, when b_0 is very small, it could give extreme values for Q_G. And when λ is big, it would result to ψ having values very different from zero as can be deduced from eq.15, which would cause large innovations that would eventually lead to divergence. Hence a choice of a reasonably small value of λ could put a heavy penalty on the increment $\{Q_G(t)-Q_G(t-1)\}$, ensuring a near zero value for $\psi(t)$.

CONCLUSIONS

STC has been found to be well suited for the optimal control of lock and dam gate openings, where the use of the controlled gate discharge results in the required upstream water level being met. Hence excessive gate discharge is minimized such that the entrance of sea water is prevented. Also the use of STC has shown that the unnecessary depletion of the reservoir during flood periods can be avoided. The satisfactory results shown in this study could serve as a basis for more applications of STC in water resources engineering. We hope to report in the near future on the investigation of the use of AKF to improve the performance of STC after transient periods (such as floods). In general, the simulation study has shown some interesting characteristics of the use of STC to the control of lock and dam gate openings.

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