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Study on the dissolved oxygen control of biotechnical treated water for agricultural irrigation

Du Xianjun*, Yu Ping, Ren Chongyu
College of Electrical and Information Engineering, Lanzhou University of Technology, Lanzhou 730050, (CHINA)
E-mail: 8843079@qq.com

ABSTRACT

In order to ensure the biochemical treated water (also known as the reclaimed water) can be safely used in agricultural irrigation, a model predictive control method is used for effective control of dissolved oxygen in the activated sludge biological wastewater treatment process. In generally, maintaining the dissolved oxygen concentration around 2 mg/L will make the activated sludge process effectively for organic pollutants removing. Simulation results under Benchmark show that the model predictive control method is better than conventional PI control method in terms of response speed, overshoot and other performance. Stable and reliable treatment process is the assurance of high quality reclaimed water out from the wastewater treatment plants, and the reclaimed water will be more suitable for agricultural irrigation. The works have important practical guiding significance.

KEYWORDS

Reclaimed Water;
Dissolved oxygen;
Model predictive control;
Agricultural irrigation.

INTRODUCTIONS

Reclaimed water (also known as the intermediate water) is a water source from city sewage after biochemical treatment, it can be used for agricultural irrigation, city greening, parks, tourists and entertainment etc. In the agricultural irrigation application, it has a mature application in Israel[1], the United States, Germany and other developed countries, in which, Israel is always in the leading position around the world in the recycling of sewage, 46% of the country's reclaimed water is directly used for irrigation, and 30% for groundwater recharge and discharged into the river for indirect reuse[2,3].

In 1985, Chinese Research and Monitoring Institute of Environmental Protection of the Department of Agricultural build up a sewage irrigated demonstration area in Yongdeng County, Gansu Province and Pengzhou City, Sichuan Province. A special subject of reclaimed water for agricultural use is set up in the Chinese "Eleventh Five Years" science and technology planning. Theory research and application practice of the reclaimed water treatment technology are applied in many cities also, and agricultural irrigation safety control laboratory and pilot demonstration base for the sewage recycling are established in Lanzhou City and the other regions in China. The "Twelfth Five Years Plan" clearly pointed out: by 2015, the sewage reuse rate will reach more than 20% all around the country. However, the sewage reuse rate in many developed countries is more than 70%. Obviously, the investment space of China's renewable water is still very wide[4].

Rational use of the reclaimed water in our city is an effective way to ease the shortage of water resources in the current and the future, and also reduce the re-pollution of the sewage[5]. Reclaimed water irrigation can supplement the agriculture irrigation water sources, saving the agricultural input costs, and increase the income of farmers. At present, more than 90% city sewage is treated by the activated sludge process. It has important practical significance to ensure the effluent water quality can meet the "standards of the irrigation water quality" and the security of reclaimed water irrigation through the research on control of the traditional activated sludge process.

The molecule oxygen in the air dissolved in water is called the dissolved oxygen (DO). The number of dissolved oxygen in water is a measure of self purification ability of water body. The control quality of the dissolved oxygen concentration plays an important role on the treatment effect of the activated sludge process. Due to the nonlinear characteristics of strong coupling, strong disturbance, and large time delay, the traditional control method is not easy to achieve good control effect of the sewage biotechnical treatment process. It leads the effluent water quality with fluctuations, and not up to the national wastewater discharge standards. According to the characteristics of the activated sludge process, model predictive control strategy is selected for the effective control of dissolved oxygen in the process in this paper. The simulation results show that the control performance is improved with the overshoot, the response time, and the stable time compared with the traditional PI strategy, and the dissolved oxygen in water quality is more stable.

PRINCIPLE AND METHOD

Model predictive control

Model Predictive Control (MPC) method is a new computer control algorithm contains the three elements of model prediction, rolling optimization and feedback correction[6] with the successful application in the oil refining, chemical industry, electric power and other complex industrial process. At present, the MPC receives the widespread attention. So, research on the corresponding theory about MPC is a hot topic in the field of control theory, and it has become the most representative method of the advanced control strategy of industrial process control.

In 1978, the heuristic model predictive control is proposed by Richalet *et al*.[7] It is a predict control algorithm that early applying to the industry process control. Its core idea is: the control strategy is based on the online optimization; the initial condition is the current state of the system at each sampling time; the response of the system is predicted through the dynamic model in finite time; then optimizing the future performance according to the model of object by solving an open loop optimization problem; the first control function of the control sequence get from the above optimization problem will put on the process object[8]. The predictive control algorithm using the online rolling optimization, and the optimization process of continuous through the actual system output and the model output difference to feedback correction, therefore, model predictive control can overcome the influence of errors of prediction model and some uncertain disturbances in a certain extent[6].

Figure 1 shows the diagram of the DO process MPC control schematics. Assume the temperature is constant in the treatment process, so in order to maintain a constant DO value in the aeration tank, the measured DO concentration by the ideal sensor[9] placed in the tank should be send to the MPC controller to compare with the DO setting value, then the MPC controller will adjust the operating variables (dissolved oxygen the mass transfer coefficient) values, which can be used to adjust the DO concentration in the pool, according to the concentration difference. Repeated prediction, optimization and feedback correction step, the concentration of DO will eventually be maintained around the set value within a certain range, to achieve DO process control target.

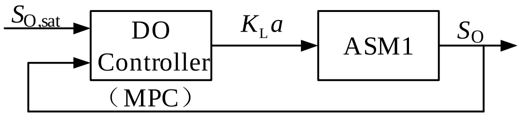

Figure 1 DO control schematics

For the assumed m steps control increment (present or future), $\Delta u(k)$, $\Delta u(k+1)$, …, $\Delta u(k+m-1)$, the p steps predictive output of the process object are $y(k+1|k)$, $y(k+2|k)$, …, $y(k+p|k)$. The present or future *m* steps control increments (*m*<*p*) are obtained by calculating the minimum value of the following second-time objective function:

$$\min_{\Delta u(k),\Delta u(k+1),\ldots,\Delta u(k+m-1)} \sum_{l=1}^{p}\left\|\Gamma_l^y[y(k+l|p)-r(k+l)]\right\|^2+\sum_{l=1}^{m}\left\|\Gamma_l^u[\Delta u(k+l-1)]\right\|^2 \quad (1)$$

And it is restricted by the following inequality:

$$\begin{aligned} &\underline{y}\le y(k+j)\le \overline{y}, && j=1,\ldots,p \\ &\underline{u}\le u(k+j)\le \overline{u}, && j=0,\ldots,m-1 \\ &\Delta\underline{u}\le \Delta u(k+j)\le \Delta\overline{u},\ j=0,\ldots,m-1 \end{aligned} \quad (2)$$

Where, and are the weight matrix used to punish specific variables in the prediction of time domain (*y* or *u*); is the future set value vector. Although in the rolling optimization process, the *m* steps control increments $\Delta u(k)$, $\Delta u(k+1)$, ..., $\Delta u(k+m-1)$ will be calculated, but only the first control increment will be executed. Therefore, in the rolling optimization process, the present control domain will move forward one step when the next sampling interval comes. The calculation process is repeated along with the new output values of the process object have been collected and the new first control increments will be executed. The optimal control problem will be realized by the repetition. But the object prediction outputs $y(k+1|k)$, $y(k+2|k)$,..., $\Delta u(k+m-1)$ are depend on the current actual output $y(k)$, assume that the effect of unmeasured disturbances and measurement noise are included in $y(k)$, so the simulation test in the following will also have man-made measured-noise added into the system output to test the effectiveness and dynamic response ability of the control strategies. And then we assume all the input variables in addition to the aeration tank are unmeasured disturbance, except the operating variable K_La.

State space model identification

Steady-state simulation data according to the different degree of aeration is simulated by the BSM1 platform in literature[10]. The continuous time state space model is established by following form:

$$\frac{dx}{dt}=Ax+Bu, \qquad y=Cx+Du \quad (3)$$

Where, *x* is the state vector; *u* and *y* respectively for the input and output vectors; *A*, *B*, *C* and *D* respectively for the state space parameter matrix.

Figure 2 is the step response curve of different aeration levels under the system identification model. In this Figure, three step response curves are built up according to the three concentration level, 2mg/l, 1.4mg/l and 0.9mg/, in the aeration tank.

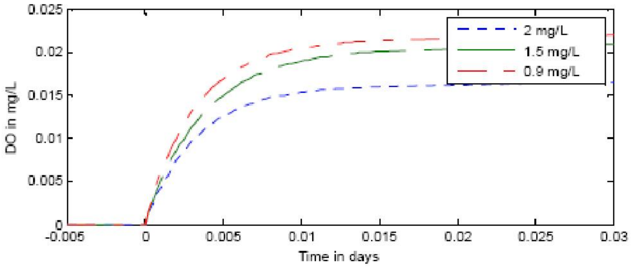

Figure 2 : Step response curve of the identification Models under different aeration level

SIMULATION TESTS

Controller performance tests

The simulation study on the response performance of controller is based on the continuous state space matrix obtained above. Controller parameters are set as follows: the sampling time $\Delta t=2.5\times10^{-4}$ day $\approx$ 20s, $\Gamma^y=1$, $\Gamma^u=0.01$, $m=1$, $p=10$. Results are the green dashed line as shown in Figure 3a. In order to verify the controller's performance, the DO set value is changed from 2mg/l to 2.3mg/l at $t=0.03$day in the test process, and at , reduced the DO concentration in influent 1mg/l. In the two cases, the controller can rapidly make the control response of DO concentration, and it is achieved good results.

At the same time, in order to validate the control performance on the different parameters of the controller parameters, parameters are adjusted as follows: in Figure 3a, red dashed line is the response curve obtained by narrowing prediction domain (*p*=6); the green dashed line is the response curve obtained by increasing the penalty weight value of input variables ($\Gamma^u=0.1$).

From the compared results in Figure 3a can be seen, reduce the prediction field can shorten the response time of the controller, but the overshoot will increase; increase the input variable penalty weight value will make the response time and overshoot increased.

The operating variables output variation is shown in Figure 3b, there are significant changes time point

$t = 0.03\text{day}$ and $t = 0.07\text{day}$ (line color and style are the same as Figure 3a), so we can get the same conclusions those be drawn in Figure 3a.

Figure 4 shows compared control performance results in different sampling time under the dry weather data from seventh to fourteenth days provided by IWA Benchmark[11]. As can be seen from the diagram, when the water flow fluctuations (disturbance) is larger, the control performance under the smaller sampling time ($\Delta t = 2.5\times10^{-4}\text{day} \approx 20\text{s}$, red line) is better than the bigger one ($\Delta t = 1\times10^{-3}\text{day} \approx 1\text{min}\ 25\text{s}$, blue dashed line), and the error is relatively small. It can be seen that the sampling time is shorter the controller performance is better. But taking into account that the larger time scale of the parameters in the biological wastewater treatment process, and the total response time of the processing system and other factors, the sampling time can not be infinitely reduced, otherwise it may cause negative effects. So we must determine the optimal sampling time value by trial-and-error method constantly.

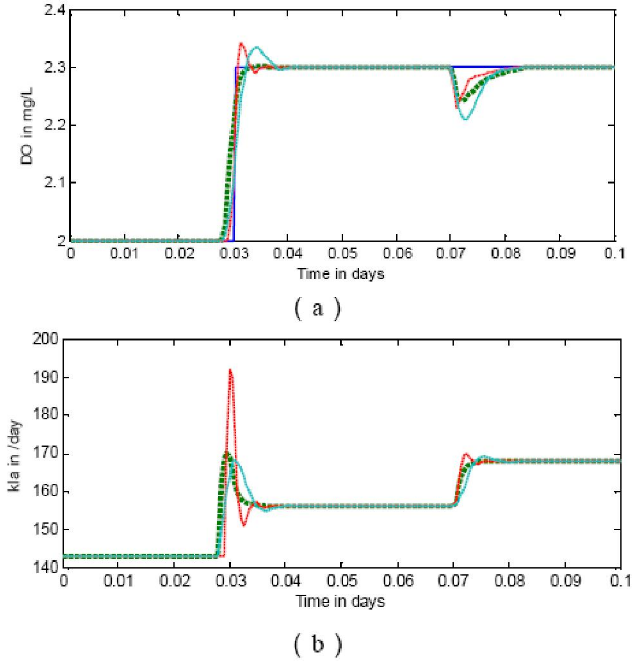

Figure 3 Controller response performance simulation results with different controller parameters

It is sure from Figure 3 and Figure 4 the controller performance is closely related with the parameters, such as the sampling time, the prediction step, and the input weights, and so on. So in the actual use of the MPC controller, we usually determine the configuration parameters in the response time, overshoot, and so on, of the controller to achieve the best performance by the trial-and-error method to repeat the procedure of parameters debugging, so that the control process can be stable and reliable.

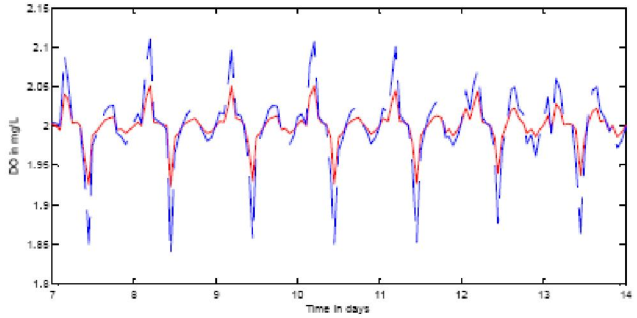

Figure 4 Controller performance simulation results with different sampling time (Δt)

Compared control performance simulation

The compared control performance simulation result under Benchmark is shown in Figure 5 (dry weather data from seventh to fourteenth days). As can be seen from Figure 5, the control performance of the method in this paper is better than PI control strategy in control precision, errors, and response time.

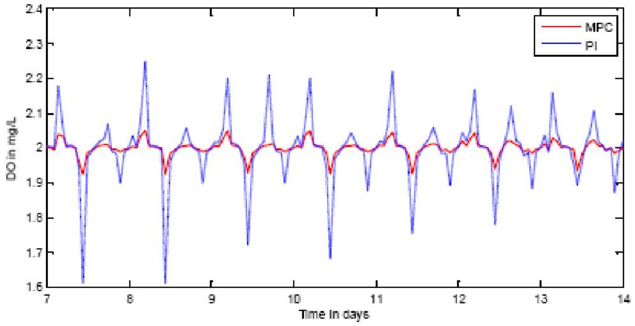

Figure 5 Compared control performance simulation results under Benchmark

CONCLUSIONS

(1) Consumption and transformation of the dissolved oxygen and the biochemical reaction process of the wastewater biotechnical treatment system are a kind of complex process with the nonlinear characteristics of strong coupling, large time delay, time-varying, and so on. Conventional control strategy is unable to realize the accurate control effect. Model predictive control is an advanced and the most rep-

resentative control strategy in the field of industrial process control, application research is studied on the dissolved oxygen control performance of the wastewater treatment process in this paper.

(2) From the simulation results of the controller performance can be seen, the control performance is closely related with the controller parameters, such as the sampling time, penalty weight, prediction step, and so on. A group of optimal parameters of the controller is determined in this paper by trial-and-error method and applied it into the control work of the activated sludge process under Benchmark.

(3) The compared control performance simulation results under the Benchmark show that the stability of DO is improved to a greater degree more than the traditional PI control strategy with smaller fluctuations. The activated sludge process is more stable and reliable, so that the treatment effect is better and the effluent quality will easy to reach the safety index of agricultural irrigation. In addition, too high aeration cost is one of the main reasons lead to the high operation cost of wastewater treatment plant. The strategy in this paper make the smaller DO fluctuation in control process, it is beneficial to the energy saving in the blower aeration operation with more stable load change. So, it can reduce the operation costs of the activated sludge process.

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