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Predictive Control of Dissolved Oxygen Concentration in Cynoglossus Semilaevis Industrial Aquaculture

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Abstract: Dissolved oxygen is an important factor that influences cynoglossus semilaevis' growth. Keeping the stability of its concentration is beneficial for cynoglossus semilaevis' healthy growth. The changing process of dissolved oxygen concentration contains nonlinearities and big time-delay because it is restricted by multiple factors, so traditional control methods are difficult to control it effectively or keep its concentration stable. This paper proposes a predictive control model for dissolved oxygen based on DMC algorithm. Firstly, it adopts DMC's predictive model to predict the dissolved oxygen concentration's variation trend. Secondly, it gives the calculated optimal control to aerators. Using DMC predictive model, it has better solved the nonlinear prediction problem of dissolved oxygen. Using DMC rolling optimization, it has better solved the optimal control problem of dissolved oxygen. System simulation results have shown that the model this paper proposed has a good performance in terms of rapidity, disturbances and errors in dissolved oxygen control. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Industrial aquaculture, Dissolved oxygen, Predictive control, DMC.

1. Introduction

Industrial aquaculture is the collection of machine, electricity, chemical, instrument, biological engineering and water treatment technology [1], actually it's a water closed circulation aquaculture factory, which is a factory for cynoglossus semilaevis' high-density breeding under manual control. It has many benefits, such as environmental protection, high yield and safety product controlled. But also because of the high density, abnormal change of some kind of survival factors will cause cynoglossus semilaevis' large area of death. Therefore, in industrial aquaculture, monitor and control the main water quality parameters which influence the growth of cynoglossus semilaevis is particularly important.

Dissolved oxygen is one of the most important factors of industrial aquaculture. Statistics have shown that dissolved oxygen concentration for cynoglossus semilaevis industrial aquaculture must be higher than 7 mg/L [2]. The growth of cynoglossus semilaevis will be suppressed when the dissolved oxygen concentration is less than 4 mg/L [3]. At present, dissolved oxygen concentration control is generally timing control or manual control, which has great randomness, for example, some farmers open the aerators all day, which will inevitably cause a lot of waste.

In industry, the commonly used control methods are PID control, fuzzy control, neural network control and predictive control, etc.

Due to the dissolved oxygen's characteristics of non-linearity and big time-delay, for dissolved oxygen control system, the conventional PID control is difficult to achieve good control effect .Fuzzy control is easy to produce wrong operation when meets larger interference. Due to a large amount of calculation, neural network control's response speed is very slow. Therefore, it is important to find a way to solve the problem of dissolved oxygen control with non-linearity and big time-delay.

2. Predictive Control of Dissolved Oxygen

2.1. Description about Dissolved Oxygen Control System in Cynoglossus Semilaevis Industrial Aquaculture

The cynoglossus semilaevis industrial aquaculture is strict with water quality and the change of dissolved oxygen is influenced by multiple factors, so the internal physical and chemical mechanism is very complex, which will lead to a consequence that the changing process of dissolved oxygen concentration can't immediately follow the controlling role of the aerator. The changing process of dissolved oxygen concentration has the characteristics of non-linearity and big time-delay, so it is difficult to establish the accurate model of dissolved oxygen controlling.

According to experiments and experience, the increasing oxygen control system can be simplified by a first-order plus dead-time system, the system can be described as:

$$G(s)=\frac{Y(s)}{U(s)}=\frac{k}{TS+1}e^{-\tau S}, \quad (1)$$

This formula means: due to the internal structure of aerator and some physical and chemical factors which influence the changing of dissolved oxygen, there is a relationship between aerator switch action and the change of dissolved oxygen concentration.

Among them, k is the total gain of the system, T is the inertia time constant of the system, and τ is the delay time of this system. This formula can be approximated to simulate the process of dissolved oxygen controlling.

In industrial aquaculture, even a short time of hypoxia can have a big impact on the growth of aquatic animals. Therefore, in the process of dissolved oxygen controlling, what people really care about are the control response speed and efficiency. In other words, the control system expects that dissolved oxygen concentration can quickly track to the set value [4].

Based on the above reasons, the whole control system needs to take a strategy which can predict the dissolved oxygen concentration at first, then according to certain indicators to control the aerator. This strategy is called predictive control which has been commonly used in industries.

2.2. Principle of the Dissolved Oxygen Predictive Control System

Predictive control is a popular and well-established control method in the process industries since the 70s, Dynamic Matrix Control (DMC), Predictive Functional Control (PFC), Preview Control (PC) and Generalized Predictive Control (GPC), neural network predictive control algorithm are commonly used [5]. Basic theory of predictive control consists three parts: predictive model, rolling optimization and feedback correction. On the basis of dissolved oxygen's characteristics of nonlinear, big time-delay, dynamic matrix control (DMC) can be applied.

DMC is an internal model control strategy based on discrete-time step response model [6]. It uses system's step response as its prediction model, meets the tracking requirement with quadratic rolling optimization Indexes [7], and it overcomes the disadvantageous factors of time-varying uncertain objects with error correction [8].

The principle of dissolved oxygen control system can be described as below (See Fig. 1).

As Fig 1 shows, ω is the set value of dissolved oxygen concentration, $u(k)$ is the optimal manipulated variable of the system, actually it is the start-stop time of aerator's switch action. $y(k)$ is the dissolved oxygen's actual value the system outputs, $y_M(k)$ is the predict value of dissolved oxygen concentration, $e(k)$ is the error between actual value and predict value of dissolved oxygen concentration, $y_p(k+i)$ is the predict value of dissolved oxygen concentration after error correcting. The whole predictive control system's purpose is to make the dissolved oxygen concentration closely tracking the set value, finally to make it stable in the level which is most beneficial to cynoglossus semilaevis' growth.

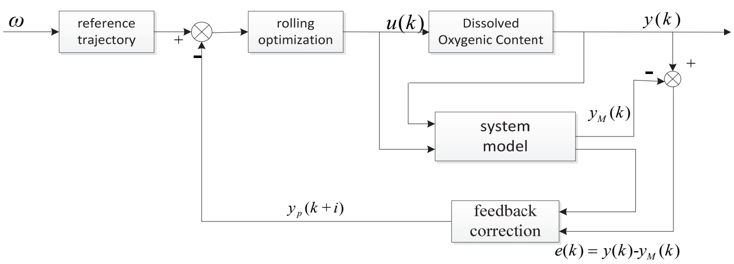

Fig. 1. Principle diagram of DMC used for DO control.

3. Dynamic Matrix Control (DMC)

3.1. DMC's Predictive Model

The predictive value of dissolved oxygen is composed by two parts, one is $y_0(k+i\,|\,k)$ which means dissolved oxygen concentration under the effect of aerator in the past, another is $A\Delta U(k)$ which means the output response of the control action at present. Where A is a matrix composed by dissolved oxygen control system's step response, it is called dynamic matrix, and

$$A=\begin{bmatrix} a_1 & 0 & \cdots & 0 \\ a_2 & a_1 & \ddots & 0 \\ \vdots & \vdots & \ddots & \\ a_P & a_{P-1} & \cdots & a_{P-M+1} \end{bmatrix}.$$

So the P step's predictive value of dissolved oxygen at $k+1$ moment is:

$$\begin{bmatrix} y_M(k+1\,|\,k) \\ y_M(k+2\,|\,k) \\ \vdots \\ y_M(k+P\,|\,k) \end{bmatrix}=\begin{bmatrix} y_0(k+1\,|\,k) \\ y_0(k+2\,|\,k) \\ \vdots \\ y0(k+P\,|\,k) \end{bmatrix}+ \begin{bmatrix} a_1 & 0 & \cdots & 0 \\ a_2 & a_1 & \ddots & 0 \\ \vdots & \vdots & \ddots & \\ a_P & a_{P-1} & \cdots & a_{P-M+1} \end{bmatrix}\begin{bmatrix} \Delta u(k) \\ \Delta u(k+1) \\ \vdots \\ \Delta u(k+M-1) \end{bmatrix}, \quad (2)$$

where M is the control horizon, P is the predictive horizon. Usually there is $M \le P$.

$\Delta U(k)$ is the continuous control incremental vector which needs to be calculated:

$$\Delta U(k)=[\Delta u(k),...,\Delta u(k+M-1)]^T \quad (3)$$

3.2. DMC's Rolling Optimization

In the process of dissolved oxygen control , the control purpose is to make the dissolved oxygen concentration in the pool track set value quickly under the switch action of aerators, and finally to make it stable in the level which is most beneficial to cynoglossus semilaeviss' growth. Therefore, control result should satisfy the following two conditions:

1) In the future P moment: $y_M(k+i) \to \omega(k+i)$.

It means dissolved oxygen's predictive value tend to be equal as the set value of dissolved oxygen concentration in the future.

2) In the future P moment: $\Delta u \to 0$.

It means control system stay stable, control variable has almost no change.

Therefore, the optimize performance indicators can be expressed by this formulation at k moment:

$$\min J(k)=\sum_{i=1}^{P} q_i\left[\omega(k+i)-y_M(k+i\,|\,k)\right]^2 + \sum_{j=1}^{M} r_j \Delta u^2(k+j-1), \quad (4)$$

where q_i and r_j are output and input weight matrixes respectively and there has $1 \le i \le P$, $1 \le j \le M$, combining equations (2) and (4), through the derivative solution

$$dJ(k)/d\Delta u_j(k)=0, \quad (5)$$

Then it can get the optimal control increment vector as

$$\Delta U_M(k)=(A^TQA+R)^{-1}A^TQ[\omega\,(k)-y_p(k)] \quad (6)$$

$\Delta U_M(k)=(\Delta u(k),...\Delta u(k+M-1))$ is the aerator's optimal control increment sequence. DMC algorithm only orientate the first control increment to compose aerator's optimal control quantity in the actual control process, the formulation is

$$u(k)=u(k-1)+\Delta u(k) \quad (7)$$

Then the N predictive value of dissolved oxygen concentration under aerator's control is:

$$\begin{bmatrix} y_1(k+1)\,|\,k \\ \vdots \\ y_1(k+N\,|\,k) \end{bmatrix}=\begin{bmatrix} y_0(k+1\,|\,k) \\ \vdots \\ y_0(k+N\,|\,k) \end{bmatrix}+\begin{bmatrix} a_1 \\ \vdots \\ a_N \end{bmatrix}\Delta u(k), \quad (8)$$

where N is the modeling horizon, its values are between 20 and 50. The next time, DMC takes a similar optimization question to calculate $\Delta u(k+1)$, so it's called rolling optimization.

3.3. DMC's Feedback Correction

In the actual control process, dissolved oxygen concentration is always affected by many natural factors, such as water temperature, air pressure, PH, ammonia nitrogen, etc. They are treated as environmental interference because of their uncontrolled characters. Furthermore, the control system is also possibly has model mismatch problem. Both of them can make the predictive value of dissolved oxygen produce big or small errors. Therefore, it is significant to use feedback correction to correct the predictive value.

$$e(k+1) = y(k+1) - y_1(k+1|k), \quad (9)$$

where $e(k+1)$ is the predictive error of dissolved oxygen at the $k+1$ moment. Using the prediction error to correct the predictive value of dissolved oxygen (do) next time is feasible

$$\begin{bmatrix} y_p(k+1|k) \\ \vdots \\ y_p(k+N|k) \end{bmatrix} = \begin{bmatrix} y_1(k+1|k) \\ \vdots \\ y_1(k+N|k) \end{bmatrix} + \begin{bmatrix} h_1 \\ \vdots \\ h_N \end{bmatrix} e(k+1), \quad (10)$$

where $h=[h_1,h_2,...,h_N]^T$ is the error correction coefficient, the value of h can be 1. $y_p(k+i)$ is the predict value of dissolved oxygen concentration after error correcting. Then it defines $y_0(k+i|k+1)$ as a new predictive value vector of dissolved oxygen concentration at the new moment through the shift calculation, this process is called status updates :

$$\begin{bmatrix} y_0(k+2|k+1) \\ y_0(k+3|k+1) \\ \vdots \\ y_0(k+N+1|k+1) \end{bmatrix} = \begin{bmatrix} 0 & 1 & & 0 \\ & \ddots & \ddots & \vdots \\ & & 0 & 1 \\ 0 & \cdots & 0 & 1 \end{bmatrix} \begin{bmatrix} y_p(k+1|k) \\ y_p(k+2|k) \\ \vdots \\ y_p(k+N|k) \end{bmatrix} \quad (11)$$

Now it's a time for the new process of predictive control, so $y_0(k+i|k+1)$ is the predictive value of dissolved oxygen at the new $k+1$ moment, and it will participate in the calculation of $u(k+1)$.

4. System Simulation

4.1. Data Acquisition of the Control System

The data acquisition module puts the PH sensors, pressure sensors, electrical conductivity sensor, water temperature sensor, and dissolved oxygen sensor in the corresponding places, and connect them to sampling node. The data collected by each sensor was send to routing node through sampling node, then routing node sends them to the monitoring center. The monitoring center use DMC algorithm to calculate the optimal control quantity of aerator, it's just the start-stop time of aerator's switch action. The purpose of the above steps is to make the dissolved oxygen concentration keeps stable at a level of which the most beneficial to the growth of cynoglossus semilaevis. The data acquisition module can be described as below (Fig. 2).

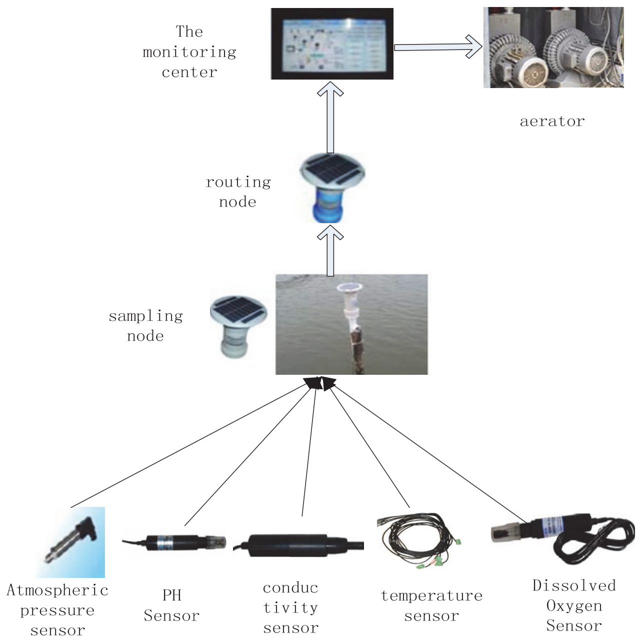

Fig. 2. Data acquisition of the control system.

4.2. DMC Algorithm and PID Algorithm for Dissolved Oxygen Control System

According to experiments and experience, in this control system, U=0.86, K=0.0157, $\tau = 30$.

Parameters need to be determined of DMC algorithm are sampling period (Ts), reference trajectory ω, the control horizon (M), the predictive horizon (P), the modeling horizon (N) and the error correction coefficient (h). In this paper, $Ts=0.5s$, $\omega=8mg/L$, $M=1$, $P=5$, $N=50$ and $h=1$ are set.

Due to the dissolved oxygen has many interference factors, and in order to make the simulation much closer to the actual dissolved oxygen control, some interferences are joined after 60 seconds of the control process. Furthermore, the DMC algorithm has been used to simulate this control system for different time-delay of the control system, they are 20 s, 30 s, 40 s, 50 s.

In order to illustrate the superiority of the DMC algorithm effect, the PID algorithm is employed to simulate the control process. Simulation results are shown in Figs. 3 and 4.

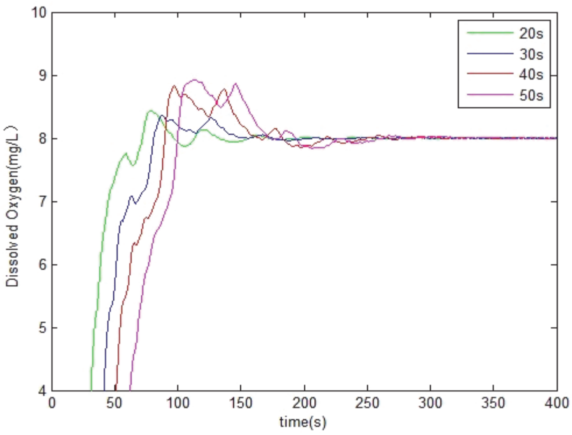

Fig. 3. DMC simulation results of the control system.

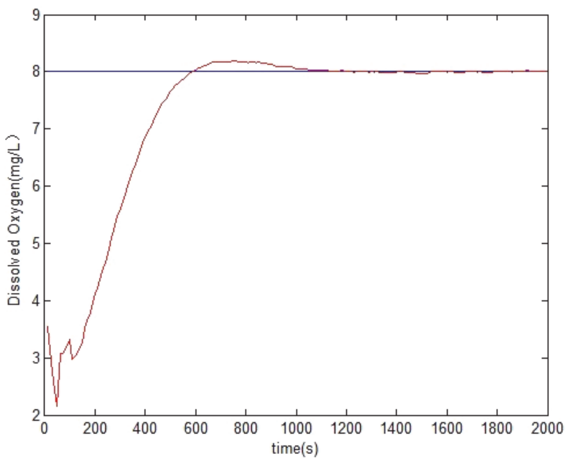

Fig. 4. PID simulation result of the control system.

4.3. Result Analysis

In contrast to the above simulation results, it is reasonable to draw the following rules：

1) The DMC predictive control can make the dissolved oxygen concentration reach 8 mg/L quickly, and the overshoot volume is small;

2) DMC's anti-interference ability is very strong, after 60 s in the time domain, the value of dissolved oxygen concentration had some shocks only a short period of time because of interference, but it tends to be stable soon;

3) The effect of simulation for the dissolved oxygen control system which has 30s time-delay is best, the tracking curve is smooth and it can quickly track the set value. The control system with 50s time-delay systems have some shocks, but the tracking curve also tends to be stable after 150 s.

4) In the control process of dissolved oxygen control system with time-delay, compared with PID control, DMC control can make the concentration of dissolved oxygen track to the set value much faster. In other words, DMC control has a better performance than PID in terms of rapidity for dissolved oxygen control system.

5. Conclusions

In cynoglossus semilaevis industrial aquaculture, the changing process of dissolved oxygen has characteristics of nonlinear and big time-delay. Many natural factors are out of control, so that traditional methods are difficult to control the dissolved oxygen concentration effectively. According to experiments and experience, the increasing oxygen control system can be simplified by a first-order plus dead-time system, and the nonlinear prediction problem of dissolved oxygen and the optimal control problem of dissolved oxygen have been better solved with using DMC predictive model. The simulation experiments confirmed that the DMC algorithm is able to cope with the given control problems. System simulation have shown that in the process of dissolved oxygen control, the DMC algorithm of this paper proposed has a good performance in terms of rapidity, disturbances and errors in dissolved oxygen control.

Therefore, the DMC algorithm can be taken into consideration for the control of dissolved oxygen concentration.

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