A FUZZY CONTROL BASED ON DISSOLVED OXYGEN MONITORING SYSTEM IN AQUACULTURE
/
基于模糊控制的水产养殖中溶解氧监控系统的研究

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Abstract: *Dissolved oxygen (DO) is a key water quality factor of aquaculture water in aquaculture. It plays an essential role in growth of aquaculture organisms. By analyzing DO monitoring system in aquaculture, a mathematical model of DO monitoring system was constructed. On the basis of fuzzy control theory, the fuzzy control of DO was realized. The simulation results show that the method proposed is feasible and convenient for application, and it is able to appropriatelyl monitor DO in water. In comparison with that , the fuzzy control based DO monitoring technique can shorten culturing period, improve culturing efficiency and reduce the cost of cultivation.*

Keywords: *aquaculture, fuzzy, dissolved oxygen, monitor, control*

INTRODUCTION

Most of living creatures on the earth cannot live without oxygen. Accounting for 21% of air ratio, oxygen presents high content and stability, so living creatures on the land are living with enough oxygen. However, DO in water (DO is molecular oxygen dissolved in water or liquid phase) shows less content and variation. Generally, The amount of saturated DO in freshwater is approximately equal to that of one-twentieth of oxygen content in the air. It is even fewer in seawater. As an indispensable element to aquatic animals and plants, DO has been one of the most concerned water quality factors. For instance, there are some common cultured fishes which live by relying on DO at present: DO content required in adult stage is of 3mg/L; when DO content is lower than 2mg/L, slight fishes hypoxia is observed; when lower than 0.8-0.6mg/L, serious fishes hypoxia is presented. Serious fish hypoxia does great harm to fishes' health. Fishes are likely to die of suffocation if DO content decreases to 0.5-0.3mg/L. Feeding rate, food utilization and weight gain rate of fishes are significantly influenced by the contents of DO. Thus, it is necessary to monitor and control DO in the aquaculture [1-5].

Nowadays, DO monitoring techniques in aquaculture can be classified into intelligent monitor, automatic monitor and experienced monitor world widely. In intelligent monitor, as a key environment factor in aquaculture water, DO and other factors (i.e. Ph and temperature etc.) are analyzed by computer. Then, environment factors in water can be controlled to perform intelligent monitor. Finally, industrialized culture can be realized. The intelligent monitor technique characterized by high production yield, as well as high cost of input and maintenance is generally applied in developed countries[6]; automatic control is mainly used in fish breading and aquaculture of rare aquatic animals which demands high to DO content. This monitor method collects DO concentration in water using sensor. Then according to the demands of fishes cultured, oxygen supplementary in water is realized by oxygen-increasing machine. This method presents low intelligence and cost. It can fulfill high production yield. Therefore, it is frequently used in aquaculture [7]. Based on the experiences of aquaculture operator on DO concentration, experienced monitor usually controls oxygenation machines and judge whether oxygen should be enriched or not in water, to sustain the growth of fishes.

***摘要**：在水产养殖中，溶解氧是养殖水体的关键水质因子，它对养殖生物的生长起着重要的作用。通过对水产养殖溶解氧监控系统进行分析，建立了溶解氧监控系统的数学模型，并借助模糊控制理论，实现了对溶解氧的模糊控制。通过仿真发现：该方法简单易行，能够较好的对水体中溶解氧的进行监控。通过与无监控系统的水产养殖对比发现：基于模糊控制的溶解氧监控技术的应用能够缩短养殖周期，提高养殖效率，降低养殖成本。*

关键词: *水产养殖,模糊,溶解氧,监测,控制.*

引言

地球上绝大多数生物都离不开氧气。约占空气比例在21%的氧气含量高而稳定，因此陆地上生物很少有缺氧的威胁。而水体中的溶解氧(溶解于水或液相中的分子态氧，DO)含量少而且多变化。一般情况下，淡水中饱和溶氧量大约相当于空气中氧气含量的 1/20，海水中则更少，因而作为水生动植物生存不可缺少的溶解氧成为水产养殖中人们最为关注的水质因子之一。目前，国内外常见的几种主要养殖鱼类，在成鱼阶段可允许的溶氧量为 3mg/L 以上，当溶氧降到 2mg/L 以下时就会发生轻度浮头，降到 0.8-0.6mg/L 时出现严重浮头，鱼类发生一次严重浮头就象生一场大病一样。如果溶氧降到 0.5-0.3mg/L 时就会窒息而死。溶氧量的大小对鱼类的摄食率、饵料利用率和鱼体增重率也都有很大影响。因此，在水产养殖中很有必要对水中的溶解氧进行监测和控制 [1-5]。

目前，国内外在水产养殖中溶解氧的监控主要分为智能化监控、自动监控和经验监控三类。智能化监控是将溶解氧作为水产养殖水体的重要环境因素之一与其它因素（如酸碱度，温度等）一起进入计算机进行分析，然后再控制水体环境因素，实施智能监控，从而实现工厂化养殖。它多应用在欧美发达国家，生产效率较高，但投入及维护的成本也较高 [6]。自动监控主要应用在育苗以及对溶解氧有较高要求的名贵水产动物的养殖上，主要是利用传感器实时采集水体中溶解氧浓度，根据养殖生物的需求，再通过充氧机对水体的氧气实施补充。这种方法智能化程度偏低，但成本较为低廉，也能实现高的生产效率，因此在水产养殖中使用较多 [7]。经验监控主要是借助养殖人员对水体溶解氧浓度的经验判断来控制充氧气机是否为养殖水体进行充氧。这种方法主要应用在常见水产生物的养殖中，因其控

This method is mainly used in cultivation of common aquatic fishes. Because it has low cost and is easy to control, it is more popular in developing countries [8,9]. The research analyzed DO monitoring system in aquaculture water and constructed a mathematical model of DO control. Based on fuzzy control theory, fuzzy control of DO was realized. This technique proposed is easy to operate and presents strong robustness. It can be a better way to control DO in water.

制方法简单，成本低廉，在发展中国家应用较为普遍 [8,9]。

本文通过对水产养殖水体溶解氧监控系统进行分析，建立了溶解氧控制的数学模型，并借助模糊控制理论，实现了对溶解氧的模糊控制。该方法简单易行，鲁棒性较强，能够较好的实现对水体溶解氧的控制。

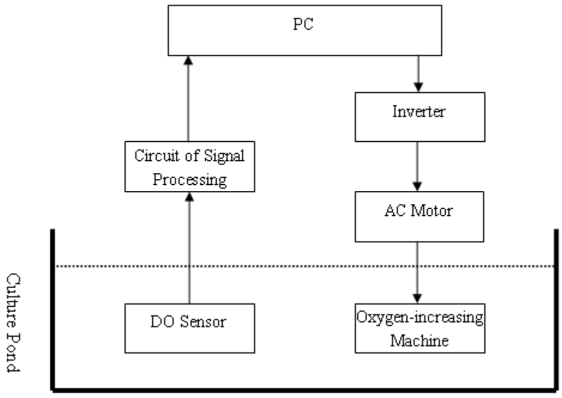

Fig. 1 - Working principle of DO monitoring system /*溶解氧监控系统工作原理图*

MATERIALS AND METHOD

Working principle of do monitoring system

In this research, automatic control is selected in the study of aquaculture DO monitor. Its working principle is illustrated in Fig. 1. This system mainly consists of culture pond, aquaculture water, PC, DO sensor, circuit of signal processing, oxygen-increasing machine, AC motor, and inverter. Its working principles are illustrated as: DO Sensor is put into the water to monitor DO concentration. Corresponding electrical signals are inputted into PC by circuit of signal processing. Those signals inputted into PC are saved for conduct analysis. Then, relative control strategies are performed by some algorithm. By controlling AC motor speed using inverter, oxygen-increasing speed of oxygen-increasing machine can be controlled. Consequently, DO content in water can satisfy the requirements of aquaculture.

材料与方法

溶解氧监控系统工作原理

本文所研究的水产养殖溶解氧监控属于自动监控类，其工作原理如图 1 所示。主要有有养殖池、养殖水体、计算机、溶解氧传感器、信号处理电路、增氧机、交流电机、变频器等组成。通过放置在养殖池水体中的溶解氧传感器监测到溶解氧浓度，将对应电信号经过信号处理电路送入计算机存储并分析，借助一定的算法实施相关的控制策略，通过变频器来控制交流电机的转速，进而实现对增氧机增氧速度的控制，使水体中的溶解氧含量满足养殖的要求。

Mathematical model

Model of DO Sensor

A Polarographic membrane electrode method is employed in this system. The cathode of electrode is made by golden plate of 4 mm. Anode, also called reference electrode, is silver plate. Electrolyte is charged between anode and cathode. The top parts of anode and cathode are covered using polytetrafluoroethylene film. After applying 0.7 V of polarization voltage between the two electrodes, oxygen which is passing through the film is reduced on golden cathode. Due to redox reaction happened on electrodes, electronic conversion produces current which shows direct ratio to oxygen partial pressure. Reactions in oxygen electrodes of polarographic membrane can be demonstrated as [10]:

数学模型

溶解氧监测系统模型

本系统采用极谱式薄膜电极法。其中，电极的阴极由 4mm 黄金片组成，阳极即参比电极为银片，两极之间充以电解液，顶端以聚四氟乙烯薄膜覆盖。当阴阳两极间加 0.7V 左右的极化电压后，渗透过薄膜的氧在黄金阴极上还原，由于电极上发生氧化–还原反应，电子的转换产生了正比于样品中氧分压的电流。极谱型薄膜氧电极的反应分别为 [10]：

$$O_2 + 2H_2O + 2e^- \rightarrow H_2O_2 + 2OH^- \tag{1}$$

$$H_2O_2 + 2e^- \rightarrow 2OH^- \tag{2}$$

$$Ag + Cl^- \rightarrow AgCl + e^- \tag{3}$$

$$4Ag + O_2 + 2H_2O \rightarrow 4AgCl + 4OH^- \tag{4}$$

Signal process circuit of DO is shown in Fig.2. The currents produced by DO sensor are converted into voltage signals. Those signals obtained are amplified to input into the DO concentration collecting card. Owing to the influence of temperature on measurement precision, temperature in measurement of DO content should be taken into account.

溶解氧信号处理电路图如图 2 所示。它将溶解氧传感器产生的电流转换为电压信号并加以放大送入数据采集卡。因为温度变化对测量的精度有一定影响，所以在溶解氧含量测量过程中要将温度考虑进去。

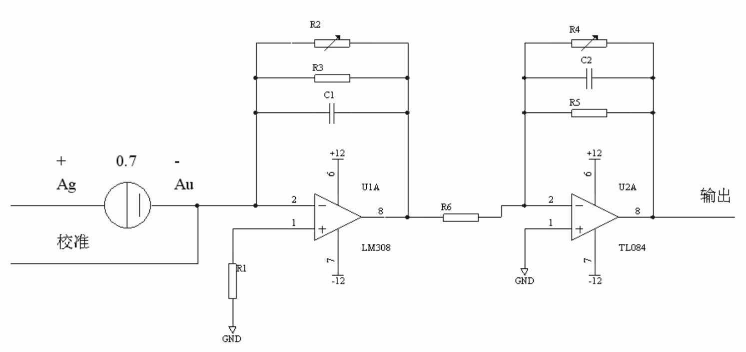

Fig. 2 - Signals process circuit of DO /*溶解氧信号处理电路图*

DO in water can be expressed as

水中溶解氧的计算公式：

$$DO_2 = DO_1[1+5\%(T_1 - T_2)] \times \frac{E_2 - E_0}{E_1 - E_0} \tag{5}$$

Where, DO_2 denotes DO content of measured solution at T₁; DO_1 indicates DO content of oxygen saturation water at temperature T_1; E_0 refers to potential value of electrodes immersed in Na_2SO_3 solution; E_1 is potential value when clean electrodes intrude into oxygen saturation water; E_2 is potential value when clean electrodes intrude into the solution to be measured; T_1 denotes oxygen saturation temperature; T_2 is the temperature of solution to be measured.

On the basis of measurement principle of oxygen meter and electrochemical equation, we obtain

其中，DO_2 为在 T_1 时被测溶液的溶解氧含量；DO_1 为氧饱和水在水温 T_1 时的溶解氧含量；E_0 为将电极浸入 Na_2SO_3 溶液内的电位值；E_1 为清洁电极侵入氧饱和水中的电位值；E_2 为清洁电极侵入待测溶液中的电位值；T_1 氧饱和水温度；T_2 被测溶液温度。

根据溶氧仪的测定原理及电化学方程式可得：

$$DO = DO_2 + \frac{r_\infty}{a} = (1 - e^{-at}) \tag{6}$$

Where DO is measured value (mg/L) of DO content at t ; r_∞ is OUT value (mg/(L × min)); a denotes the electrode response speed parameter of oxygen meter (min^{-1}), $a = 9.2\,\mathrm{min}^{-1}$.

其中，DO 为 t 时刻溶解氧含量的实测值（mg/L）；r_∞ 为实际 OUT 值（mg/(L×min)）；a 为溶氧仪电极响应速度的参数（min^{-1}），此处取 $a = 9.2\,\mathrm{min}^{-1}$。

Model of DO Control [11]

DO control are more influenced by environment. Before constructing mathematical mode, it is assumed that: culture pond is a small indoor pond (10m×10m×2m); the living creatures cultured in the pond are the only factors consuming DO; Only oxygen-increasing machine can be used to supplement DO in water. Temperature in cultured pond and Ph are constant. After satisfying conditions above mentioned, concentration variation of DO in water is expressed

溶解氧控制系统模型[11]

溶解氧的控制受环境因素的影响较多，在建立数学模型之前，需要做以下假设。养殖池为室内小型池（10m×10m×2m），池中除养殖的生物外无其它因素消耗池中溶解氧，池中溶解氧只能通过增氧器来增加，另外养殖池温度和酸碱度均为恒定值。在满足上述条件后，水中溶解氧浓度的变化率可用如下公式表示

$$\frac{dy(t)}{dt} = \frac{Q(t)}{V}[y_{in} - y_{out}] + K_L a(u(t))[y_{sat} - y(t)] - K_t y(t) \tag{7}$$

Where, Q is air flow, $Q(t) = K_q N(t)$. $N(t)$ indicates the motor speed. K_q is coefficient of air flow; V is volume of culture pond; $y(t)$ is DO concentration; y_{in} is oxygen concentration of air inputted; y_{out} is oxygen concentration of air outputted; $y_{sat}(t)$ is saturated DO concentration; $K_L a(u(t))$ is function of oxygen conversion, its change is linear with the variation of air flow. Taking K_n as a constant, K_t denotes the constant of DO consumption rate. By conducting Laplace transform on formula (8).

其中，Q 为空气流量，$Q(t) = K_q N(t)$，$N(t)$ 为电机转速，K_q 为空气流量系数；V 为养殖池容积；$y(t)$ 为溶解氧浓度；y_{in} 为输入空气的氧浓度；y_{out} 为输出空气的氧浓度；$y_{sat}(t)$ 为饱和溶解氧浓度；$K_L a(u(t))$ 为氧气转换函数，它的大小与空气流量的变化呈非线性关系，这里将其看作一个常数 K_n；K_t 为溶解氧消耗速率常数。对公式（7）作拉普拉斯变换得公式（8）。

$$Y(S)S = \frac{K_q N(S)}{V}(y_{in} - y_{out}) + K_n[y_{sat} - Y(S)] - K_t Y(S) \tag{8}$$

The transfer function of the system is

那么，系统的传递函数为：

$$G(S)=\frac{Y(S)}{N(S)}=\frac{K_q(y_{in}-y_{out})/V}{S+K_n+K_t} \qquad (9)$$

If $K_q(y_{in}-y_{out})/V=U$, and $K_n+K_t=K$, $G(S)=\dfrac{U}{S+K}$ is obviously a first order inertial link.

若令 $K_q(y_{in}-y_{out})/V=U$，$K_n+K_t=K$，显然，$G(S)=\dfrac{U}{S+K}$ 是一个一阶惯性环节。

System Model

By detecting the system model, the results shows that monitoring of DO is non-linear and presents delay characteristic. Formula (6) and (9) are used to remedy such shortfall. τ refers to monitoring delay. While, Formula (9) is remedied

溶解氧监控系统模型

由检测系统模型可知，溶解氧的监测是非线性，具有滞后特性。利用公式（6）对（9）进行修正，将监测滞后用 τ 来表示，则公式（9）修正为：

$$G(S)=\frac{U}{S+K}e^{-\tau s} \qquad (10)$$

Formula (10) can be approximately described as an simulation model of DO monitoring system. On the basis of experiences and experiments, $U=0.82$, $K=0.0157$ and $\tau=40$ in simulation model are obtained.

式（10）可近似认为是溶氧监控系统的仿真模型。依据经验和试验可得仿真模型中的 $U=0.82$，$K=0.0157$，$\tau=40$。

Fuzzy control

Definition of Variables

According to DO model in aquaculture, there are two inputs in the system: the differences, also named as deviation e of DO and set value measured by sensor is first input; another one is variation ratio et of DO. Output is motor speed n of oxygen-increasing machine. The motor speed can be controlled based on e and et. Consequently, DO of culture pond is stabilized to set value.

Fuzzy Method

DO model takes e which is deviation of DO content value and set value and measured by sensor as an input. With fuzzy domain being [-3，3], the difference of DO content value and set value can be measured.

模糊控制

定义变量

根据水产养殖池中溶解氧模型可知，系统的输入有两个，一个为传感器测得的溶解氧与设定值的差值即偏差 e，另一个为测得溶解氧变化率 et，输出为增氧机电机的转速 n。系统根据 e、et 的情况来控制电机转速，使养殖池中溶解氧稳定在设定值。

模糊化

根据溶解氧模型可知，取传感器测得的溶解氧值与设定值的偏差 e 为输入量，取模糊论域为[-3，3]，代表测得溶解氧值与设定值之差。

Table1 / *表 1*

Saturated DO in the water temperature / *不同温度下水中溶解氧含量*

Temperature(℃)/*温度*	**Saturated DO (mg/L) / *饱和溶解氧含量***
0	14.64
5	12.74
10	11.26
15	10.08
20	9.08
25	8.25
30	7.56
35	6.95

Assuming temperature in culture pond is 20~30℃ with freshwater in the pond, as shown in table 1, saturated DO content is about 8mg/L, while, commonly controlled DO content is 7mg/L. The experiences show that fuzzy domain above-mentioned can satisfy the control requirement. The fuzzy variables correspond to seven classes [-3,-2,-1, 0, 1, 2, 3]. The classes are indicated as seven subsets based on membership function. Using assignment of fuzzy variables, the fuzzy variables symbols are expressed as NL, NB, NM, Z, PM, PB and PL. They represents maximum, large value, negative median, no deviation, positive median, positive large value and positive maximum of negative e respectively. The membership function is shown in Fig.3. NL is membership function of Z type; PL is membership function of S type, the rest five subsets are triangle membership function.

这里，假定养殖池温度为 20~30 摄氏度，池中为淡水。如表 1 所示，此时的饱和溶解氧含量大约在 8mg/L 左右，而一般控制的溶解氧浓度大约在 7mg/L 左右，依据经验上述模糊论域可满足控制要求。将模糊变量与 7 个等级[-3,-2,-1,0,1,2,3]对应，依据隶属度函数将等级表示为 7 个模糊子集，采用模糊变量赋值，模糊变量符号表示为 NL、NB、NM、Z、PM、PB、PL，其含义为偏差 e 为负的最大值、大值、负的中值、无偏差、正的中值、正的大值、正的最大值。其隶属度函数参照图 3 所示，NL 为 Z 型隶属度函数、PL 为 S 型隶属度函数，其它五个为三角形隶属度函数。

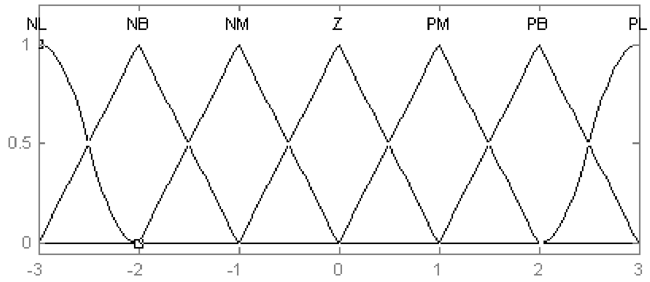

Fig. 3 - The membership function of DO deviation / *溶解氧偏差的隶属度函数*

The variation rate of DO is an important input parameter. Based on experiences, fuzzy domain [-0.3 , 0.3] of DO variation rate et are selected to have fuzzy variables corresponding to seven classes [-0.3,-0.2,-0.1,0,0.1,0.2,0.3]. According to membership function, the seven classes denotes as seven fuzzy subsets. Based on assignment of fuzzy variables, the fuzzy variables symbols are expressed as NL, NB, NM, Z, PM, PB and PL respectively. Those symbols refer to the decrease of fastest rate, fast rate and medium rate, constant, the increase of medium rate, fast rate and fastest rate in DO vibration rate respectively. The membership function is illustrated in Fig.4. NL is membership function of Z type; while, PL is membership function of S type, the rest five subsets are triangle membership function.

溶解氧的变化速率也是重要的输入参数，依据经验，取溶解氧变化率 et 的模糊论域为[-0.3，0.3]，将模糊变量与 7 个等级[-0.3,-0.2,-0.1,0,0.1,0.2,0.3]对应，依据隶属度函数将等级表示为 7 个模糊子集，采用模糊变量赋值，模糊变量符号表示为 NL、NB、NM、Z、PM、PB、PL，其含义为溶解氧变化率最快速变小、快速变小、中速变小、不变、中速变大、快速变大、最快速变大。其隶属度函数参照图 4 所示，NL 为 Z 型隶属度函数、PL 为 S 型隶属度函数，其它五个为三角形隶属度函数。

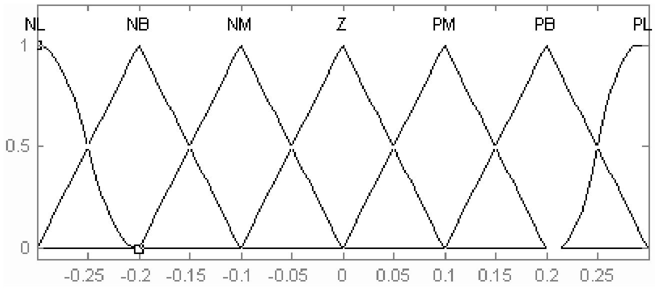

Fig. 4 - The membership function of DO variation / *溶解氧变化率的隶属度函数*

On the basis of working principle of oxygen-increasing machine, DO shows direct ratio to motor speed. In this case, motor speed can be adjusted to control the increase rate of DO. The fuzzy domain of oxygen-increasing machine motor speed n is [0 , 6] which represents coefficient of motor speed. The coefficient multiplied by maximum speed can obtain real motor speed. Corresponding fuzzy variables to seven classes [0,1,2,3,4,5,6] , the classes are demonstrated as seven fuzzy subsets based on membership function. According to assignment of fuzzy variables, the symbols of fuzzy variables are Z, VS, VMS, VM, VBM, VB and VL. They represent zero speed, low speed, low-medium speed, medium speed, large and medium speed, large speed and maximum speed respectively. The membership function is shown in Fig.5. Z is membership function of Z type; VL is membership function of S type, while, the rest five subsets are triangle membership function.

根据增氧机的工作原理可知，溶解氧与电机转速为正比关系，这样就可以通过调整电机转速来控制溶解氧增加的快慢。增氧机电机的转速 n 的模糊论域为 [0，6]，代表电机转速系数，它乘于最大转速即可得到当前电机转速。将模糊变量与 7 个等级[0,1,2,3,4,5,6]对应，依据隶属度函数将等级表示为 7 个模糊子集，采用模糊变量赋值，模糊变量符号表示为 Z、VS、VMS、VM、VBM、VB、VL 其含义为转速零、低转速、中低转速、中转速、大中转速、大转速、最大转速。其隶属度函数参照图 5 所示，Z 为 Z 型隶属度函数、VL 为 S 型隶属度函数，其它五个为三角形隶属度函数。

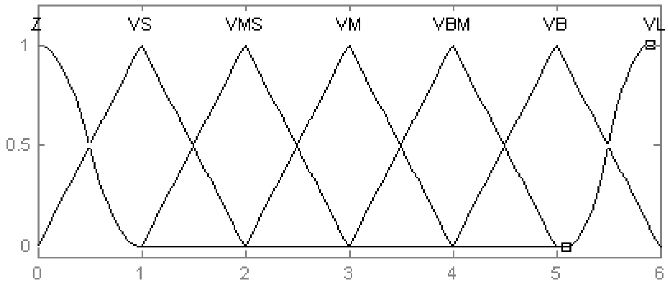

Fig. 5 - The membership function of motor speed / *增氧器电机转速的隶属度函数*

Fuzzy rule

Based on characteristics of aquaculture, four empirical rules of controlling DO in aquaculture are obtained as follows:

(a) IF DO is smaller than set value THEN motor rotates.
(b) IF DO is larger than set value THEN motor stops working.
(c) IF DO decreases THEN motor speed increases.
(d) IF DO increases THEN motor speed decreases.

The difference variation measured of DO content and set value, and variation rate of DO mainly rely on that specific variable corresponds to fuzzy subset. The relative control rules can be illustrated using fuzzy conditional statement as:

IF e=NL AND et=NL THEN u=VL
IF e=NL AND et=NB THEN u=VB
…
IF e=PL AND et=NL THEN u=Z
IF e=PL AND et=NB THEN u=Z
…

Based on analysis abovementioned, 49 control rules can be abbreviated as one rule table of fuzzy control, as shown in table 2.

模糊控制规则

针对水产养殖的特点，得到水产养殖溶解氧控制的四条总体经验规则：

（a）IF 溶解氧小于预定值 THEN 电机转
（b）IF 溶解氧大于等于预定值 THEN 电机停
（c）IF 溶解氧下降 THEN 电机增速
（d）IF 溶解氧上升 THEN 电机减速

具体测得溶解氧与预定值的偏差的大小，溶解氧变化率的大小，主要依赖具体数值所对应在模糊子集。相应的控制规则可用如下模糊条件语句来描述：

IF e=NL AND et=NL THEN u=VL
IF e=NL AND et=NB THEN u=VB
…
IF e=PL AND et=NL THEN u=Z
IF e=PL AND et=NB THEN u=Z
…

依次类推，所有 49 条控制规则可以简写成一个模糊控制规则表，如表 2 所示。

Table 2 / *表 2*

The control rules / *控制规则表*

Speed(n) / *转速*		**Variation ratio (et) / *变化率***						
		NL/*最快速变小*	**NB/*快速变小***	**NM/*中速变小***	**Z / *不变***	**PM/*中速变大***	**PB/*快速变大***	**PL/*最快速变大***
Deviation (e) / *偏差*	**NL/*负的最大值***	VL	VB	VBM	VM	VMS	VS	Z
	NB/*负的大值*	VB	VBM	VM	VMS	VS	Z	Z
	NM/*负的中值*	VBM	VM	VMS	VS	Z	Z	Z
	Z/*无偏差*	VM	VMS	VS	Z	Z	Z	Z
	PM/*正的中值*	VMS	VS	Z	Z	Z	Z	Z
	PB/*正的大值*	VS	Z	Z	Z	Z	Z	Z
	PL/*正的最大值*	Z	Z	Z	Z	Z	Z	Z

Fig.6 displays 3-D relationship of inputs e, et, and output n based on the rules.With the decrease of e and et, n increases; when e, et and n are NL, NL and VL, the motor speed is fastest, the oxygen-increasing speed of oxygen-increasing machine reaches to maximum; when both e and et are zero, n is zero and motor stops working; Only when e is large and et is small, n is not expected to be zero. Otherwise, n is zero; when e is small, n increases with the decrease of n. All these results are in agreement with DO control rule in aquaculture water.

如图 6 所示，为输入 e 和 et 与输出 n 在上述模糊规则下的三维关系图。随着 e 和 et 的减小，输出 n 将增大。当 e 为 NL，et 为 NL 时，n 为 VL，这时电机转速最高，增氧机增氧速度达到最快。当 e 和 et 都等于零时，输出量 n 即为零，即电机停止工作。当 e 较大时，只有在 et 较小时，n 不为零，否则 n 为零；当 e 较小时，随着 et 变小时，则 n 变大。这些都符合水产养殖水体中溶解氧的控制规律。

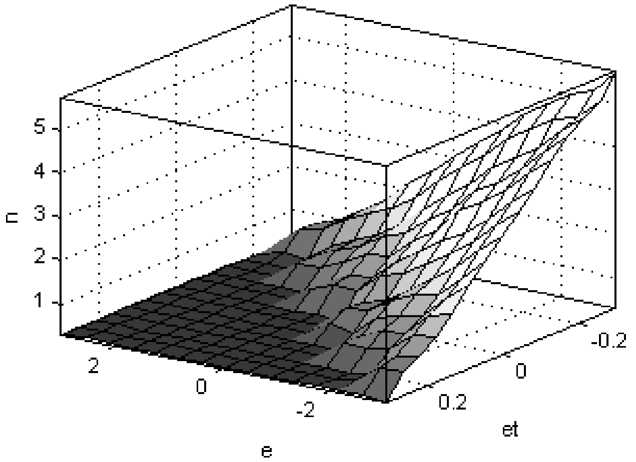

Fig. 6 - The rule relationship of input and output / *输入与输出规则关系图*

Defuzzification

Fuzzy values outputted are multiplied by motor speed factors (300), motor speed required to be controlled is obtained. The value of speed control is transferred to inverter. Motor speed can be thereof controlled to further control the DO content in aquaculture water.

反模糊化

根据输出的模糊值，乘于电机速度因子（300），就得到所需控制的电机速度，然后将要控制速度值送给变频器，控制电机转速，达到控制水产养殖水体中溶解氧含量的目的。

RESULTS

SIMULATION AND EXPERIMENTS

Simulation

On the basis of mathematical model of DO in aquaculture, the DO monitoring system of aquaculture was conducted simulation by using fuzzy logic toolbox and SIMULINK of MATLAB [12].

结果

仿真与实验

仿真

在水产养殖溶解氧数学模型的基础上，借助于 MATLAB 软件中的模糊逻辑工具箱和 SIMULINK，对水产养殖溶解氧监控系统进行仿真分析 [12]。

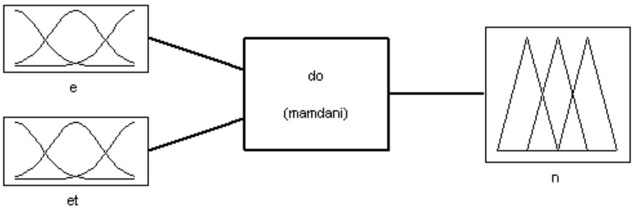

Fig. 7 - Relationship of input and output / *模糊控制输入输出关系*

Fig. 7 shows the relationship of input and output of fuzzy control. Using 3 editors in fuzzy logic toolbox including Fuzzy inference system editor, Membership function editor, and Fuzzy rule editor, the rules of input, output, and fuzzy control are set by referring Figs.3, 4, 5, and 6.

图 7 为模糊控制输入输出关系图。借助模糊逻辑工具箱里的 3 个编辑器（模糊推理系统编辑器、隶属函数编辑器、模糊规则编辑器）设置好输入、输出以及模糊控制规则，可参考图 3、4、5 和 6。

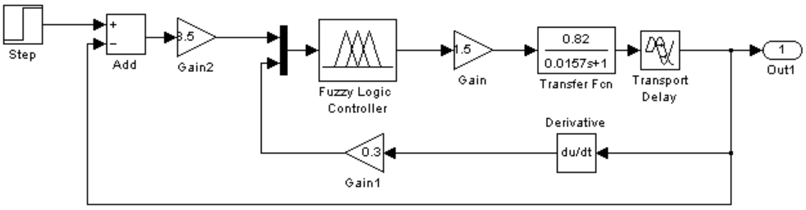

Fig. 8 - Simulation frame of control system /*控制系统仿真框图*

As shown in Fig.8, SIMULINK is used to establish the simulation mode of the system. DO is set to 7mg/L (substituted by step signal, with the amplitude of 7); meanwhile, some gain links are added in the system. Corresponding gain values are set by experiment.

如图 8 所示，借助 SIMULINK 工具建立系统的仿真模型，溶解氧设定值为 7mg/L（以阶跃信号代替，幅值为 7），在系统中加入了一些增益环节，通过实验设定好相关增益值。

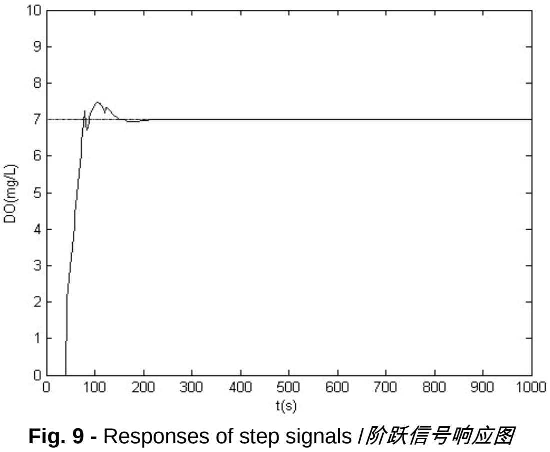

Fig. 9 - Responses of step signals /*阶跃信号响应图*

Fig. 9 shows the responses of step signals with amplitude o f 7 at 1,000 seconds. The figure indicates that the system delays 40 seconds. Such delay is decided by the characteristics of DO sensor and large inertia in the

图 9 为系统阶跃响应图，幅值为 7，时间为 1000 秒。可看出系统的有 40 秒的延时，这是系统溶解氧传感器特性以

system. Fine adjustment is presented when the response is equal or larger than 7mg/L. It takes about 70 seconds for it to reach the maximum; the response is stabilized to about 7mg/L. The step response of the system shows that the system presents advantages such as stability, precision, small overshoot and fast response.

及整个系统的大惯量特性决定的。响应在达到并超过 7mg/L 时很快有一个微调，并且上升到最大值的耗时大约为 70 秒，响应很快就稳定在 7mg/L 左右。通过系统的阶跃响应图看出，系统是稳定精确的，超调量很小，响应速度较快。

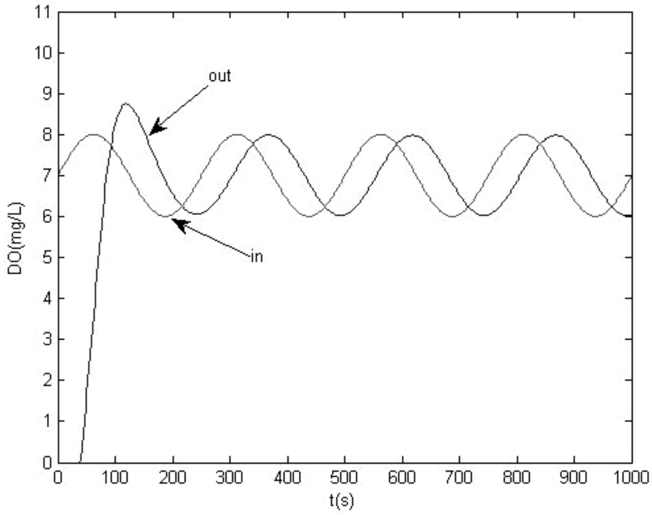

Fig. 10 - Responses of sinusoidal signal / *正弦信号响应图*

Fig.10 displays the responses of sinusoidal signals. The sinusoidal signal with amplitude of 1, deviation of 1, the circle of 250 s and simulation time at 1,000 s is taken as input signal. Fig.10 shows that comparing with input, output delays about 40 s. This is consistent with that of step response. In first response circle, input does not fit well with output in the system. But output begins to response input precisely since second circle. This phenomenon indicates the control system presents strong robustness.

Experiments

Culture pond is indoor type with 10 m, 10m and 2m in length, width, and depth respectively. The mandarin fish is selected for culturing. The comparative experiments are conducted in two ponds. Traditional oxygenation machine is used to supplement oxygen within 24 h in the first pond; while, in the second pond, the system proposed is used to monitor DO in water. The optimal temperature of mandarin fish's growth and feeding is set to the range of 23～28°C. With water temperature at 26°C, optimum DO in water is 7mg/L. It is a culture period for the mandarin fish grows about 7 months (for sale in market), with its weights of 500 g. The same amount of mandarin fishes is put into two ponds respectively. After culturing 7 months, the results are shown in table 3.

图 10 为系统正弦信号响应图。选用幅值为 1，偏差为 7，周期为 250 秒的正弦信号作为输入信号，仿真时间为 1000 秒。从图 10 中可看出，输出相对于输入有 40s 左右的滞后，这与阶跃响应情况吻合。在响应的第一周期，系统的输出与输入吻合度不高，但在从第二个周期开始，输出都能准确地反应输入，这说明该控制系统的鲁棒性是较强的。

实验

养殖池为室内池，长宽深分别为 10m、10m 和 2m。养殖鱼类主要为鳜鱼。分别在两个养殖池里做对比试验，一个养殖池采用传统的充氧机全天对水体补充氧气，一个是利用本论文所提方法对养殖池水体进行溶解氧监控。因为鳜鱼生长摄食的最佳温度在 23～28℃之间，池内水温逗控制在 26℃，水体的最佳养殖溶氧量为 7mg/L。7cm 左右的鳜鱼长到 500g 左右（可以上市销售）是一个养殖周期，大概需要 7 个月。对两个养殖池投放相同数量的鳜鱼，经 7 个月的养殖后，结果如表 3 所示。

Table 3 / ***表 3***

Comparison of culture effect / ***养殖效果对比表***

Comparison parameters / ***对比参数***	**No monitoring /** ***无监控***	**Fuzzy monitoring /** ***模糊监控***
Growing period of reaching the weights of 500 g (Month) / ***平均达到 500 克需要的时间(月)***	7	6
Total weight of mandarin fish after culturing 7 months (kg) / ***7 个月后养殖鳜鱼的总重量(公斤)***	290	390
Power consumption per month(kW/h) / ***平均每月消耗电能(千瓦时)***	1543	961

After five months culturing, 10 mandarin fishes are randomly selected in two ponds for every 10 days. Those fishes selected are weighed and their average weights are calculated. The weights of fishes in the pond without the monitoring system are smaller than that of the pond with the monitoring system. In the pond without monitoring system, it takes 7 months for the weights of fishes reaching to 500 g, while, the weights of the fishes in the pond with the fuzzy monitoring system reach to 500 g in less than 6 months. The culture period is shortened about one month. After culturing 7 months, mandarin fishes in two ponds are weighed respectively. Comparing the fishes in the pond without the monitoring system, the total weights of fishes in the pond with the monitoring system is 100 kg more than that of the pond without the monitoring system.

It is apparently found that DO content in culturing pond with fuzzy monitoring system is stabilized to the optimum value (7mg/L). This is very favorable to the growth of mandarin fish. Comparing with the powder consumptions of oxygenation instruments in two ponds, the power consumption of fuzzy monitoring system is obviously lower and onlyabout 62.3% to that of the power consumption without monitoring system. The system greatly reduces the culture cost.

CONCLUSIONS

By analyzing monitoring system and control system of dissolved oxygen in aquaculture respectively, a mathematical model of dissolved oxygen monitoring system was constructed. Then, by applying fuzzy control into monitoring system of dissolved oxygen, a fuzzy control based dissolved oxygen monitoring system was established.

The system proposed was simulated using MATLAB. The simulation results show that stability, rapidity and accuracy of the system can satisfy the control requirements.

The comparison experiments show that comparing with aquaculture without the dissolved oxygen monitoring system, the fuzzy control based on dissolved oxygen monitoring system can shorten culturing period, improve culturing efficiency and reduce the cost of cultivation.

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鳜鱼在养殖5个月后，每10天随机在这两个养殖池里选择10条鳜鱼，称重并算出平均重量。无监控系统的养殖池里的鳜鱼重量比采用模糊监控系统的养殖池里的鳜鱼轻，在养殖了7个月后平均重量才达到500g。而采用了模糊监控系统的养殖池里的鳜鱼在接近6个月时已经打到了500g，养殖周期缩短了一个月。在养殖了7个月后，将两个养殖池的鳜鱼全部称重发现，采用模糊监控系统与无监控系统相比，养殖池所养鳜鱼总重量多了100kg。

很显然，采用模糊监控系统的养殖池的溶解氧基本稳定在最佳值7mg/L左右，非常有利于鳜鱼的生长。对两个养殖池充氧设备的耗电量统计发现，采用模糊监控的耗电量明显降低，大约为无监控系统的耗电量的62.3%，这大大减少了养殖成本。

结论

通过分别对水产养殖中溶解氧监测系统和控制系统进行分析，建立了溶解氧监控系统的数学模型，并在此基础上，将模糊控制应用到溶解氧监控系统，建立了基于模糊控制的溶解氧监控系统。

利用MATLAB仿真工具对系统进行仿真发现，系统的稳定性、快速性和准确性都能够达到控制要求。

通过对比实验发现：与无监控系统的情况相比，利用溶解氧模糊控制技术能缩短养殖周期，提高养殖效率，降低养殖成本。

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