

赤潮生物种群模型的自适应变结构控制器设计

Research on Adaptive Variable Structure Control for Biological Model of Red Tide

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摘要:【目的】为进一步改进有害藻和有益藻的消长控制模型,更好控制有害藻的发生,避免其所造成的危害。【方法】假设赤潮有害藻密度可测,有益藻密度不可测,在有害藻和有益藻密度模型正则化的基础上,设计神经网络观测器来估计有益藻对应的变量;然后,设计变结构控制使有害藻浓度减少而有益藻浓度增大,最终达到稳定状态。【结果】仿真分析结果显示,有害藻和有益藻持续在稳定的状态。【结论】变结构控制器的设计合理有效。

关键词:赤潮 生物种群模型 径向基函数神经网络 变结构控制

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Abstract:【Objective】In order to overcome the weakness of traditional treatment methods of red tide(including physical method and chemical method), biological treatment technique was explored, where the relationship among creature competition, biological inhibition and biological predation was evaluated. Introducing beneficial creature in the area of red tide could inhibit the eruption of red-tide algae, and reduce the occurrence of red-tide algae and its damage. 【Methods】In the paper, we assumed that the density of harmful algae could be measured whereas the density of beneficial algae could not be measured. Based on the regularization of the density model of harmful algae and beneficial algae, neural network viewer was designed to estimate corresponding changes of beneficial algae. Then, a variable structure control was designed to reduce the density of harmful algae and increase that of beneficial algae, and finally to reach a steady state. 【Results】Simulation results of an example illustrated the effectiveness of the proposed method. 【Conclusion】The designed variable structure control is effective.

Key words: red tide, biological population model, radial basis function neural network, variable structure control

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0 引言

【研究意义】赤潮频繁,不仅严重破坏海洋生态平衡,恶化海洋环境,危害海洋水产资源,危及海洋生

物,甚至威胁着人类的健康和生命安全^[1-2]。导致赤潮的原因多种多样,比如工业废水和生活污水的排放;海洋资源的过度开发;人为因素所导致的外来物种的侵入;以及全球气候变暖等等,故加快对赤潮发生机理和治理技术的研究显得尤为重要^[3-7]。【前人研究进展】对赤潮发生机制机理的研究,不仅可以详细了解赤潮生物的行为学,生理学及形态学特征,而且还能够了解赤潮与海洋中某些物质之间的联系。因此有必要用数学模型来刻画赤潮发生发展变化的规律^[8]。引发赤潮的生物种类繁多,爆发机制各异,

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对于很多赤潮的发生机理尚未掌握,因此难以从发生机理上控制该类赤潮的发生。为了减少赤潮造成的损失,另一个主要的研究方向集中在监测和预报赤潮灾害,以及如何选择快速有效控制赤潮的方法。控制赤潮的方法有很多,比较传统的方法有物理和化学方法^[3]。物理方法对环境的影响很小,但是物理方法只能暂时减轻赤潮的危害,无法从根本上治理赤潮。化学方法可迅速控制赤潮,但是成本高,而且化学物质难以被环境自身消耗,因此所施用的化学药剂很可能会给环境造成二次污染。新兴的技术主要是生物治理技术,利用生物的竞争、抑制或捕食等关系,在赤潮发生区域引入有益生物,抑制有害藻的大量繁殖,减少危害^[8]。目前对于赤潮的防治,基本上还是以防为主,争取从源头上控制赤潮发生,减少赤潮发生的频率。由于海洋面积巨大,加上潮流和风浪的影响,因此在赤潮爆发后再进行治理,难度很大。目前实验中探索治理赤潮的方法,主要是从理论角度进行设计,距离实际的应用还有一定距离。【本研究切入点】现有的赤潮生物种群模型还未能达到理想效果,需加以改进以更好控制赤潮。文献^[4]首次研究基于广义 Logistic 赤潮模型的变结构控制,为赤潮防治提供了新的变结构控制方法。【拟解决的关键问题】本文提出了一种改进的赤潮生物种群模型,先通过变换将现有赤潮生物种群模型(有害藻和有益藻的消长控制模型)正则化^[4-5];然后,考虑到有益藻密度不可测量,利用神经网络设计有益藻密度观测器^[9-14];最后,利用变结构控制原理设计控制器控制有害藻和有益藻的数量^[15-18],并构建的 Lyapunov 函数,证明模型的稳定性^[19-21]。

1 问题描述

1.1 模型及控制目标

有害藻和有益藻的消长控制动态模型^[3]为

$$\begin{aligned} \dot{x}_1(t) &= x_1(t)(k_1 - \alpha_1 x_1(t) - \gamma x_1(t)x_2(t)^2), \\ \dot{x}_2(t) &= x_2(t)(k_2 - \alpha_2 x_2(t)) + \frac{x_1(t)}{x_2(t)}u(t), \end{aligned} \quad (1)$$

其中, $x_1(t)$, $x_2(t)$ 分别为有害藻和有益藻的密度; k_1, k_2 分别为有害藻和有益藻的最大环境容纳量; α_1, α_2 分别为有害藻和有益藻类的竞争系数; γ 是无害赤潮对有害藻的细胞接触杀灭作用系数; $\frac{x_1(t)}{x_2(t)}$ 是控制作用系数,它与有害藻密度成正比,与有益藻成反比。

本文主要控制目标是通过设计控制器 u , 以达到消除有害藻对生态系统的不良影响。

1.2 模型正则化

为了方便控制器的设计,先对模型(1)正则化,以得到可控正则模型。

对模型进行坐标平移:

$$\begin{aligned} \bar{x}_1 &= x_1 - 0, \\ \bar{x}_2 &= x_2 - k_2/\alpha_2, \end{aligned}$$

有

$$\dot{\bar{x}} = A(\bar{x}) + b(\bar{x})u, \quad (2)$$

其中

$$\bar{x} = \begin{pmatrix} \bar{x}_1 \\ \bar{x}_2 \end{pmatrix}, b(\bar{x}) = \begin{pmatrix} 0 \\ \frac{\bar{x}_1}{\bar{x}_2 + \frac{k_2}{\alpha_2}} \end{pmatrix},$$

$$A(\bar{x}) =$$

$$\begin{pmatrix} \bar{x}_1(k_1 - (\alpha_1 + \frac{\gamma k_2^2}{\alpha_2})\bar{x}_1 - \frac{2\gamma k_2}{\alpha_2}\bar{x}_1\bar{x}_2 - \gamma\bar{x}_1\bar{x}_2^2) \\ -\alpha_2\bar{x}_2(\bar{x}_2 + \frac{k_2}{\alpha_2}) \end{pmatrix}.$$

对模型(2),根据变结构控制原理,设计控制器 u , 以达到消除有害藻对生态系统的不良影响。模型(2)正则化需要满足一定的条件,为此,给出如下引理。

引理 1.1 模型(2)可通过状态变换 $\bar{x} \rightarrow \tilde{x}$ 化为可控正则型的充要条件为

1) 矩阵

$$R(\bar{x}) = \begin{pmatrix} R_1(\bar{x}) \\ R_2(\bar{x}) \end{pmatrix} = (b(\bar{x}) \quad b_A^{(1)}(\bar{x})) \quad (3)$$

满秩,其中 $b_A^{(1)}(\bar{x}) = \nabla A(\bar{x})b(\bar{x}) - \nabla b(\bar{x})A(\bar{x})$, $\nabla = (\partial/\partial\bar{x}_1 \quad \partial/\partial\bar{x}_2)^T$;

2) $[R(\bar{x})]^{-1}$ 末行 $[R_2(\bar{x})]^{-1}$ 存在相应的原函数。

这样,基于引理 1.1 的条件,模型(2)可化为相应的可控正则型。

为此,令

$$\tilde{x}_1 = \frac{1}{4\gamma x_1^2},$$

$$\tilde{x}_2 = -\frac{1}{2\gamma x_1^2}(k_1 - (\alpha_1 + \frac{\gamma k_2^2}{\alpha_2})\bar{x}_1 - \frac{2\gamma k_2}{\alpha_2}\bar{x}_1\bar{x}_2 - \gamma\bar{x}_1\bar{x}_2^2). \quad (4)$$

对(4)式求导,模型(2)变为可控正则型:

$$\begin{pmatrix} \dot{\tilde{x}}_1 \\ \dot{\tilde{x}}_2 \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \tilde{x}_1 \\ \tilde{x}_2 \end{pmatrix} + \begin{pmatrix} 0 \\ \beta(\tilde{x}) \end{pmatrix} + \begin{pmatrix} 0 \\ 1 \end{pmatrix} u, \quad (5)$$

其中

$$\begin{aligned} \beta(\bar{x}) &= \frac{1}{\gamma x_1^2} [k_1 - \frac{\bar{x}_1}{2}(\alpha_1 + \frac{\gamma k_2^2}{\alpha_2}) - \frac{\gamma k_2}{\alpha_2}\bar{x}_1\bar{x}_2 - \\ & \frac{\bar{x}_1\bar{x}_2^2}{2}] [k_1 - (\alpha_1 + \frac{\gamma k_2^2}{\alpha_2})\bar{x}_1 - \frac{2\gamma k_2}{\alpha_2}\bar{x}_1\bar{x}_2 - \gamma\bar{x}_1\bar{x}_2^2] + \end{aligned}$$

$$\frac{\alpha_2 \bar{x}_2}{x_1} (\bar{x}_2 + \frac{k_2}{\alpha_2})^2.$$

2 控制器设计

控制器的设计主要分为两部分,首先设计神经网络观测器来观测有益藻的密度;然后给出基于观测器的滑模变结构控制器。

2.1 观测器的设计

引理 2.1 对正则模型(5),分别用 \hat{x}_1, \hat{x}_2 来估计 \tilde{x}_1, \tilde{x}_2 ,用 $\tilde{X}_1 = \tilde{x}_1 - \hat{x}_1, \tilde{X}_2 = \tilde{x}_2 - \hat{x}_2$ 表示估计误差。建立如下观测器:

$$\begin{aligned} \dot{\xi}_1 &= \hat{x}_2 + k_1 \tilde{X}_1, \\ \dot{\xi}_2 &= \hat{f}_1(\tilde{x}_1, \tilde{x}_2) + k_2 \tilde{X}_1 + u, \end{aligned} \quad (6)$$

其中, $\hat{f}_1(\tilde{x}_1, \tilde{x}_2) = \hat{W}^T \hat{\varphi} = \hat{W}^T \varphi(\tilde{x}_1, \tilde{x}_2)$ 为函数 $f(\tilde{x}_1, \tilde{x}_2) = W^T \phi(\tilde{x}_1, \tilde{x}_2) + \epsilon$ 的神经网络估计值, k_1, k_2 为设计的正常数。则估计值 \hat{x}_1, \hat{x}_2 可写为

$$\begin{aligned} \hat{x}_1 &= \xi_1, \\ \hat{x}_2 &= \xi_2 + k_3 \tilde{x}_1. \end{aligned} \quad (7)$$

如果神经网络权向量 W 由以下方式调节 $\dot{W} = -\hat{W} = F\phi\tilde{X}_2$,那么估计误差 \tilde{X}_1, \tilde{X}_2 一致最终有界,且可通过选择适当增益使其充分小。

证明 由式(6)和式(7)可得

$$\begin{aligned} \dot{\tilde{x}}_1 &= \tilde{x}_2 - k_1 \tilde{x}_1, \\ \dot{\tilde{x}}_2 &= f_1 - \hat{f}_1 - k_2 \tilde{x}_1 - k_3 \dot{\tilde{x}}_1 = W^T \phi + \epsilon - \end{aligned}$$

$$\hat{W}^T \phi^T - (k_2 - k_1 k_3) \tilde{x}_1 - k_3 \tilde{x}_2 = W^T \tilde{\phi} + \tilde{W}^T \hat{\phi} + \epsilon - (k_2 - k_1 k_3) \tilde{x}_1 - k_3 \tilde{x}_2, \quad (8)$$

其中 $\tilde{W} = W - \hat{W}, \tilde{\phi} = \phi - \hat{\phi}$ 。

选取李雅普诺夫函数

$$V = \frac{1}{2} \tilde{W}^T F^{-1} \tilde{W} + \frac{1}{2} \tilde{X}_1^2 + \frac{1}{2} \tilde{X}_2^2. \quad (9)$$

对 V 求导可得

$$\begin{aligned} V' &= \tilde{W}^T F^{-1} \dot{\tilde{W}} + \tilde{X}_1 \dot{\tilde{X}}_1 + \tilde{X}_2 \dot{\tilde{X}}_2 = \tilde{X}_1 (\tilde{X}_2 - k_1 \tilde{X}_1) + \tilde{X}_2 [W^T \tilde{\phi} + \tilde{W}^T \hat{\phi} + \epsilon - (k_2 - k_1 k_3) \tilde{X}_1 - k_3 \tilde{X}_2] + \tilde{W}^T F^{-1} \dot{\tilde{W}} \\ &= -k_1 \tilde{X}_1^2 - k_3 \tilde{X}_2^2 - (k_2 + 1 - k_1 k_3) \tilde{X}_1 \tilde{X}_2 + \tilde{X}_2 (\tilde{W}^T \tilde{\phi} + \epsilon) + \tilde{W}^T (F^{-1} \dot{\tilde{W}} + \varphi \tilde{X}_2). \end{aligned} \quad (10)$$

因为 $|\tilde{X}_1 \tilde{X}_2| \leq \frac{1}{2} \tilde{X}_1^2 + \frac{1}{2} \tilde{X}_2^2, \dot{\tilde{W}} = -F\phi\tilde{X}_2$ 且

$$\begin{aligned} |W^T \tilde{\phi} + \epsilon| &< \xi, \text{ 所以} \\ V' &\leq - (k_1 - \frac{k_2 + 1 - k_1 k_3}{2}) \tilde{X}_1^2 - (k_2 - \end{aligned}$$

$$\begin{aligned} \frac{k_2 + 1 - k_1 k_3}{2} \tilde{X}_2^2 + |\tilde{X}_2| \xi &\leq - (k_1 - \frac{k_2 + 1 - k_1 k_3}{2}) \tilde{X}_1^2 - (k_2 - \frac{k_2 + 1 - k_1 k_3}{2}) \tilde{X}_2^2 + \frac{1}{2} \xi^2. \end{aligned} \quad (11)$$

由(11)式可知,当 $k_1 > \frac{k_2 + 1 - k_1 k_3}{2}, k_2 > \frac{k_1 + 2 - k_1 k_3}{2}$,且下式中有一个成立

$$|\tilde{x}_1| \geq \sqrt{\frac{\xi^2}{2k_1 - k_2 - 1 + k_1 k_3}}, \quad (12)$$

$$|\tilde{x}_2| \geq \sqrt{\frac{\xi^2}{2k_2 - k_2 - 2 + k_1 k_3}}, \quad (13)$$

所以 V' 在 \tilde{X}_1, \tilde{X}_2 的一闭合邻域之外小于零, \tilde{X}_1, \tilde{X}_2 一致最终有界,且可通过选择适当增益使其充分小。

2.2 变结构控制器的设计

定理 2.1 对模型(5),设计控制器

$$u = -\hat{f}_1 - l_1 \hat{x}_2 - l_2 \text{sgn}(S), l_2 > 0, \quad (14)$$

其中 $S = \dot{\tilde{x}}_1 + l_1 \tilde{x}_1, l_1 > 0$,使得 \tilde{x}_1 与 \tilde{x}_2 一致最终有界且可通过适当选择增益使其充分小。

证明 容易得到

$$\begin{aligned} \dot{S} &= \dot{\tilde{x}}_1 + l_1 \dot{\tilde{x}}_1 = \dot{\tilde{x}}_2 + k_1 \dot{\tilde{X}}_1 + l_1 (\dot{\tilde{x}}_2 + k_1 \tilde{X}_1) = \hat{f}_1 + k_2 \tilde{X}_1 + k_3 \dot{\tilde{X}}_1 + u + k_1 \dot{\tilde{X}}_1 + l_1 (\hat{x}_2 + k_1 \tilde{X}_1) = \hat{f}_1 + l_1 \hat{x}_2 + u + (k_2 + l_1 k_1) \tilde{X}_1 + (k_1 + k_3) \dot{\tilde{X}}_1. \end{aligned}$$

将(14)式代入上式得

$$\dot{S} = -l_2 \text{sgn}(S) + (k_2 + l_1 k_1) \tilde{X}_1 + (k_1 + k_3) \dot{\tilde{X}}_1. \quad (15)$$

由引理 2.1 可知, \tilde{X}_1 与 \tilde{X}_2 一致最终有界,且可通过适当选择增益使得 $\tilde{X}_1, \dot{\tilde{X}}_1$ 充分小。所以由(15)式可知 S 一致最终有界,而由 S 定义可得 \tilde{x}_1 与 \tilde{x}_2 一致最终有界。从而 \tilde{x}_1 与 \tilde{x}_2 一致最终有界且可通过适当选择增益使其充分小。

3 仿真分析

采用计算机数值仿真来验证控制算法的有效性。根据文献[3-4,8],模型(1)中的系数取值为 $k_1 = 0.06, k_2 = 0.63, a_1 = 5.32 \times 10^{-5}, a_2 = 8.9 \times 10^{-4}, \gamma = 5.0 \times 10^{-12}, c = 0.5, k = 1000, \epsilon = 3.0 \times 10^{-7}$ 得有害藻种群和无害藻种群的时间响应如图 1 所示。

由图 1 可以看出,经过变结构控制后,模型(1)中的有害藻和有益藻持续在稳定的状态。由此可以看出,变结构控制在这类赤潮生物种群模型的应用是可

行有效。

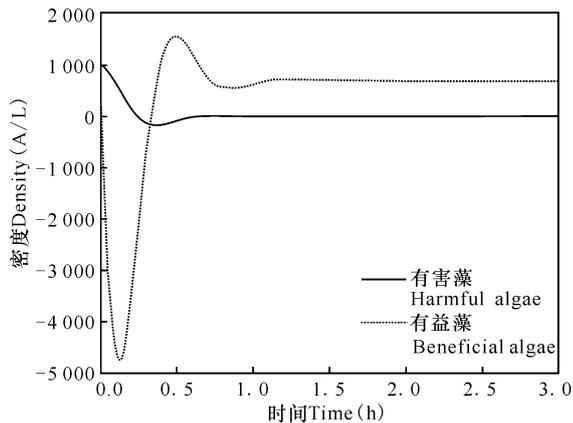


图1 模型(1)的时间响应

Fig.1 Time response of model(1)

4 结论

本文主要提出一种将 RBF 神经网络与变结构控制结合起来的方法,以此为基础建立一个赤潮模型,并根据李氏稳定性理论,分析模型的稳定性,将模型化为可控正则型,通过外部施加控制,达到模型的稳定状态。最后通过 Matlab 软件仿真,给出施加条件后系统的仿真图,验证施加控制的正确性、合理性。

参考文献:

[1] 侍茂崇,陈波. 涠洲岛东南部海域高浓度氮和磷的来源分析[J]. 广西科学, 2015, 22(3): 237-244.
SHI M C, CHEN B. Tracking the source of high concentration nitrogen and phosphorus water in the southeast of Weizhou Island[J]. Guangxi Sciences, 2015, 22(3): 237-244.

[2] 齐衍萍,杨晓飞,宋文鹏,等. 胶州湾海域生态问题及解决对策[J]. 广西科学院学报, 2015, 31(2): 94-96.
QI Y P, YANG X F, SONG W P, et al. Ecological problems and countermeasures of Jiaozhou Bay[J]. Journal of Guangxi Academy of Sciences, 2015, 31(2): 94-96.

[3] 黄姿,朱白婢,孙建波,等. 赤潮的生物防治及研究进展[J]. 安徽农学通报, 2008, 14(15): 82-85.
HUANG Z, ZHU B B, SUN J B, et al. Progresses of research on the biological control method of red tide[J]. Anhui Agricultural Science Bulletin, 2008, 14(15): 82-85.

[4] 梅光,赵聪,赵立纯,等. 基于广义 Logistic 赤潮模型的变结构控制[J]. 鞍山师范学院学报, 2012, 14(4): 7-11.
MEI G, ZHAO C, ZHAO L C, et al. Variable structure control of the red tide model with general logistic

growth[J]. Journal of Anshan Normal University, 2012, 14(4): 7-11.

[5] 王寿松. 单种群生长的广义 logistic 模型[J]. 生物学报, 1990, 5(1): 21-25.
WANG S S. A generalized logistic model of single populations growth[J]. Journal of Biomathematics, 1990, 5(1): 21-25.

[6] 邱耀文,朱良生,李锦蓉,等. 赤潮过程浮游植物与营养物质时间变化率研究[J]. 应用生态学报, 2003, 14(7): 1127-1130.
QIU Y W, ZHU L S, LI J R, et al. Temporal dynamics of phytoplankton and nutrients during red tides[J]. Chinese Journal of Applied Ecology, 2003, 14(7): 1127-1130.

[7] CHATTOPADHAYAY J, SARKAR R R, MANDAL S. Toxin-producing plankton may act as a biological control for planktonic blooms—field study and mathematical modeling[J]. Journal of Theoretical Biology, 2002, 215: 333-344.

[8] 廖欣星. 多种群赤潮非线性动力学生态模型的研究[J]. 赣南师范学院学报, 2006(6): 37-40.
LIAO X X. Research on ecological model of multi-population red tide based on the theory of non-linearity differential equation[J]. Journal of Gannan Teachers College, 2006(6): 37-40.

[9] 沈清,胡德文,时春. 神经网络应用技术[M]. 长沙:国防科技大学出版社, 1993.
SHEN Q, HU D W, SHI C. Neural Network Application Technology [M]. Changsha: National University of Defense Technology Press, 1993.

[10] 赵振宇. 模糊理论和神经网络的基础与应用[M]. 北京:清华大学出版社, 1997.
ZHAO Z Y. The Basis and Application of Fuzzy Theory and Neural Network[M]. Beijing: Tsing Hua University Press, 1997.

[11] 韩立群. 人工神经网络教程[M]. 北京:北京邮电大学出版社, 2006.
HAN L Q. Artificial Neural Networks Tutorial[M]. Beijing: Beijing University of Posts and Telecommunications Press, 2006.

[12] 陈丽华,臧荣鑫,王宏伟. 人工神经网络及其在水质信息检测中的应用[M]. 北京:国防工业出版社, 2011.
CHEN L H, ZANG R X, WANG H W. Artificial Neural Network and Application in the Detection of Water Quality Information[M]. Beijing: National Defense Industry Press, 2011.

[13] 沈世镒. 神经网络系统理论及其应用[M]. 北京:科学出版社, 2000.
SHEN S Y. Neural Network System Theory and Application[M]. Beijing: Science Press, 2000.

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parison of Ag deposition effects on the photocatalytic activity of nanoparticulate TiO₂ under visible and UV light irradiation [J]. Journal of Photochemistry and Photobiology A: Chemistry, 2004, 163(1/2): 37-44.

- [41] BESSEKHOUD Y, ROBERT D, WEBER J V. Synthesis of photocatalytic TiO₂ nanoparticles: Optimization of the preparation conditions [J]. Journal of Photochemistry and Photobiology A: Chemistry, 2003, 157(1): 47-53.
- [42] YU J G, ZHAO X J. Effect of surface treatment on the photocatalytic activity and hydrophilic property of the sol-gel derived TiO₂ thin films [J]. Materials Research Bulletin, 2001, 36(1/2): 97-107.
- [43] BECK J S, VAURTLI J C, ROTH W J, et al. A new family of mesoporous molecular sieves prepared with liquid crystal templates [J]. Journal of the American Chemical Society, 1992, 114(27): 10834-10843.

- [44] YIN J B, ZHAO X P. Enhanced electrorheological activity of mesoporous Cr-doped TiO₂ from activated [J]. The Journal of Physical Chemistry B, 2006, 110(26): 12916-12925.
- [45] ANANDAN S, SATHISH KUMAR P, PUGAZHENTHIRAN N, et al. Effect of loaded silver nanoparticles on TiO₂ for photocatalytic degradation of acid red 88 [J]. Solar Energy Materials and Solar Cells, 2008, 92(7): 929-937.
- [46] SUBRAMANIAN V, WOLF E, KAMAT P V. Semiconductor-metal composite nanostructures. To what extent do metal nanoparticles improve the photocatalytic activity of TiO₂ films? [J]. The Journal of Physical Chemistry B, 2001, 105(46): 11439-11446.

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(上接第 166 页 Continue from page 166)

- [14] 蔡如钰. 基于人工神经网络的夜光藻密度预测模型 [J]. 中国环境监测, 2001, 17(6): 52-55.
CHAI R Y. Artificial neural network predicting model of noctiluca scintillans density and physical and chemical parameters [J]. Environmental Monitoring in China, 2001, 17(6): 52-55.
- [15] 高为炳. 变结构控制理论基础 [M]. 北京: 中国科学技术出版社, 1990.
GAO W B. The Theory of Variable Structure Control [M]. Beijing: Science and Technology of China Press, 1990.
- [16] 胡跃明. 变结构控制理论与应用 [M]. 北京: 科学出版社, 2003.
HU Y M. Variable Structure Control Theory and Application [M]. Beijing: Science Press, 2003.
- [17] 姚琼荃, 黄继起, 吴汉松. 变结构控制系统 [M]. 重庆: 重庆大学出版社, 1997.
YAO Q H, HUANG J Q, WU H S. The Variable Structure Control Systems [M]. Chongqing: Chongqing University Press, 1997.

- [18] 胡剑波, 庄开宇. 高级变结构控制理论及应用 [M]. 西安: 西北工业大学出版社, 2008.
HU J B, ZHUANG K Y. Advanced Variable Structure Control Theory and Application [M]. Xi'an: Northwestern Polytechnical University Press, 2008.
- [19] 高为炳. 非线性控制系统导论 [M]. 北京: 科学出版社, 1988.
GAO W B. Introduction on Linear Systems [M]. Beijing: Science Press, 1988.
- [20] ZIRILLI A, ROBERTS G N, TIANO A, et al. Adaptive steering of a containership based on neural networks [J]. Int Journal of Adaptive Control and Signal Processing, 2000, 14: 849-873.
- [21] POWELL M J D. Radial Basis Functions for Multivariable Interpolation: A Review [M]. New York: Clarendon Press, 1987.

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