Anti-Saturation Control of Marine Planktonic Ecological Hybrid System with Saturation Based on Linear Matrix Inequality Approach

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Abstract—**By using linear matrix inequality approach, this paper considers the problem of anti-saturation control for marine planktonic ecological hybrid system with saturation. A new marine plankton ecosystem model is established. By analyzing the dynamic characteristics of the model, a stable condition is obtained in terms linear matrix inequality. The anti-saturation controller design method is designed. A numerical simulation is been given to verify the proposed approach.**

Index Terms—**Marine planktonic ecosystem, hybrid System, saturation, linear matrix inequality**

I. Introduction

Marine plankton is the basis of marine productivity. In recent years, due to the serious impact of human factors on the ecosystem and the direct or indirect impact of natural climate, the marine environment has been seriously degraded. Therefore, it is of great significance to predict and control the development trend of planktonic ecosystem [1–3]. In recent years, scholars at home and abroad have focused on the establishment of ecological models to observe the development of species through numerical simulation [4–6]. For example, in references [7-8], Feng and Wang studied the nonlinear dynamic characteristics, stability and bifurcation problems of planktonic ecosystem, modeled the marine planktonic ecosystem as a nonlinear dynamic system, and analyzed the system performance by using Lyapunov stability theory. In reference [9], the homotopy analysis method is used to simulate the marine planktonic ecosystem. Although the dynamic constraints and data constraints are considered and a large number of parameters are estimated, this method is computationally expensive and difficult to implement. The purpose of this paper is to find a more simple and effective method to simulate the system model. Herrmann et al. established a three-dimensional physical-biological-geochemical coupling model based on the interannual changes and atmospheric winter conditions, and performed statistical and budget analysis [10]. Schartau et al. studied the problem of parameter identification in the modeling of marine planktonic ecosystems [11].

Saturation phenomenon exists widely in various practical control systems. In essence, any system has different degrees of saturation constraints [12–14]. If the saturation is not considered, the system performance will be degraded or even unstable in serious cases [15–17]. In 1960s, Fuller firstly proposed the saturation system, and adopted the strategy of feedback calculation and tracking to make the system quickly exit the saturation region. In recent decades, actuator saturation control has been widely concerned by many scholars [18–19]. About the saturated network system, Zhou et al. considered the problem of the observer-based output feedback control for networked systems with actuator saturation [20]. In references [21], Zhao et al. considered the stabilization problem for saturated networked system. By updating steps of control signal of the networked control system, a state feedback controller is designed by a cone complementary linearization approach. However, the Lyapunov function designed in the above literature lacks the appropriate parameter matrix in the research process of saturated time-delay system, and the results are conservative. In addition, the influence of external interference or uncertainty on the system is not considered, so the planktonic ecosystem model is not perfect. It is difficult to realize because of the large amount of calculation.

Because of this, the purpose of this paper is to find a more simple and effective method to study the stability and other dynamic properties of the planktonic ecosystem model. In this paper, a nonlinear dynamics model of marine planktonic ecosystem with saturation is established by using the hybrid dynamics theory, and its stability and control are studied by using Networked control approach. It can provide scientific basis for marine management department to formulate marine development strategies and development plans, so as to ensure the healthy and sustainable development of marine ecosystem.

II. Modelling and Preliminaries

With the following assumptions have been given in reference [22]: (1) plankton follows the logistic growth model, and considers the weakening effect of human fishing behavior and the pollution caused by human fishing behavior on the survival of plankton; (2) the pollution caused by human fishing behavior and the fishing behavior itself have a

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negative impact on the total fishing amount; (3) the plankton ecosystem has certain self-purification capacity. The hybrid dynamic model of marine planktonic ecosystem is proposed as follows:

$$\begin{aligned}\frac{d\hat{x}}{dt} &= \hat{a}\hat{x}(1-\frac{\hat{x}}{\hat{k}}) - \hat{c}\hat{x}\hat{y} - \hat{\lambda}\hat{x}\hat{z} \\ \frac{d\hat{y}}{dt} &= \hat{\delta}\hat{c}\hat{x}\hat{y} - \hat{b}\hat{y}\hat{z} - \hat{\gamma}\hat{y} \\ \frac{d\hat{z}}{dt} &= \hat{h}\hat{z}\hat{y} - \hat{\varepsilon}\hat{z}\end{aligned} \tag{1}$$

where $\hat{x}(t)$ is the total amount of plankton, $\hat{z}(t)$ is the pollution caused by human fishing behavior, $\hat{y}(t)$ is the catch, $\hat{a}(>0)$ is the internal growth rate of plankton, $\hat{k}(>0)$ is the carrying capacity of plankton, $\hat{c}(>0)$ is the reduction rate of the total amount of plankton with the increase of fishing frequency, $\hat{\lambda}(>0)$ is the reduction rate of the total amount of plankton caused by the pollution caused by human fishing behavior, $\hat{\delta}(>0)$ is the utilization efficiency of plankton in the systems, $\hat{b}(>0)$ is the reduction rate of the pollution caused by human fishing behavior to the fishing frequency, $\hat{\gamma}(>0)$ is the fishing intensity, $\hat{h}(>0)$ is the pollution rate caused by the increase of fishing frequency, $\hat{\varepsilon}(>0)$ is the purification rate of the ecosystem.

The system (1) can be changed as:

$$\dot{x}(t) = Ax(t) + f_1(t)$$

where

$$x(t) = \begin{bmatrix}\hat{x}(t)\\ \hat{y}(t)\\ \hat{z}(t)\end{bmatrix}$$

$$A = \begin{bmatrix}\hat{a} & 0 & 0\\ 0 & -\hat{\gamma} & 0\\ 0 & 0 & -\hat{\varepsilon}\end{bmatrix}$$

$$f_1(t) = \begin{bmatrix}-\frac{\hat{a}}{\hat{k}}\hat{x}^2 - \hat{c}\hat{x}\hat{y} - \hat{\lambda}\hat{x}\hat{z}\\ \hat{\delta}\hat{c}\hat{x}\hat{y} - \hat{b}\hat{y}\hat{z}\\ \hat{h}\hat{z}\hat{y}\\ \end{bmatrix}$$

With the influence of external uncertainties and saturation, the hybrid model of marine planktonic ecosystem is obtained:

$$\begin{aligned}\dot{x}(t) &= (A+\Delta A(t))x(t) + (B+\Delta B(t))sat(u(t)) \\ x(t) &= \phi(t)\end{aligned} \tag{2}$$

where $A \in \mathrm{R}^{n\times n}$, $B \in \mathrm{R}^{n\times m}$ are constant matrix, $x(t) \in \mathrm{R}^{n}$ are systems states, $u(t) \in \mathrm{R}^{m}$ are control input, $\phi(t) \in \mathrm{R}^{n}$ is the given initial state.

The saturation function

$sat(u(t)) = [sat(u_1(t)), sat(u_2(t)), \cdots, sat(u_m(t))]$,

where

$$sat(u_i(t)) = \begin{cases}\underline{u}_i & u_i(t) \le \underline{u}_i < 0\\ u_i(t) & \underline{u}_i \le u_i(t) \le \overline{u}_i\\ \overline{u}_i & 0 < \overline{u}_i \le u_i(t)\end{cases}$$

$\Delta A(t), \Delta B(t)$ are uncertainty satisfying

$$\begin{aligned}\Delta A(t) &= D_1 F(t) E_1\\ \Delta B(t) &= D_2 F(t) E_2\\ F^T(t)F(t) &\le I\end{aligned} \tag{3}$$

Remark1. In the past, the research on marine planktonic eco dynamic system focused on the analysis of linear system. In the system (2), the influence of external disturbance on the system was considered, and the influence of controller saturation on control design and system performance was considered.

The following controller will be designed

$$u(t) = 2Kx(t) \tag{4}$$

where $K \in \mathrm{R}^{m\times n}$ is a constant matrix.

With (3) and (2), the closed-loop system can be obtained

$$\begin{aligned}\dot{x}(t) &= \overline{A}(t)x(t) + \overline{B}(t)\eta(t)\\ x(t) &= \phi(t)\end{aligned} \tag{5}$$

where

$$\begin{aligned}\overline{A}(t) &= A + BK + \Delta A(t) + \Delta B(t)K\\ \overline{B}(t) &= B + \Delta B(t)\\ \eta(t) &= sat(2Kx(t)) - Kx(t)\end{aligned} \tag{6}$$

$$\eta^T(t)\eta(t) \le x^T(t)K^TKx(t) \tag{7}$$

III. Results

Lemma1 [8]. For a given n-order symmetric matrix

$$S = \begin{bmatrix}S_{11} & S_{12}\\ S_{21} & S_{22}\end{bmatrix}$$

where S_{11} is r-order matrix, then the following three conditions are equivalent

(1) $S < 0$,

(2) $S_{11} < 0,\ \ S_{22} - S_{12}^T S_{11}^{-1} S_{12} < 0$,

(3) $S_{22} < 0,\ \ S_{11} - S_{12} S_{22}^{-1} S_{12}^T < 0$.

Lemma2 [11]. For the given constant matrix Y, D and E with appropriate dimension, where Y is symmetric matrix, then $Y + DEF + E^TF^TD^T < 0$ for matrix F satisfying $F^TF \le I$, if and only if there is a constant $\varepsilon > 0$, such that:

$$Y + \varepsilon DD^T + \varepsilon^{-1}E^TE < 0$$

Theorem1. If there are matrix $K \in R^{m\times n}$, positive matrix $P \in \mathrm{R}^{n\times n}$ and constant $\varepsilon > 0$, the following inequality holds

$$\begin{bmatrix}\overline{A}^T(t)P + P\overline{A}(t) + \varepsilon K^TK & P\overline{B}(t)\\ * & -\varepsilon I\end{bmatrix} < 0 \tag{8}$$

the system (5) is stable.

Proof: constructing the following Lyapunov function

$$V(t) = x^T(t)Px(t)$$

where $P \in \mathrm{R}^{n\times n}$ is a positive matrix.

Then, we have

$$\dot{V}(t) = x^T(t)(P\overline{A}(t) + \overline{A}^T(t)P)x(t) + 2x^T(t)P\overline{B}(t)\eta(t)$$
$$= \begin{bmatrix} x(t) \\ \eta(t) \end{bmatrix}^T \begin{bmatrix} P\overline{A}(t) + \overline{A}^T(t)P & P\overline{B}(t) \\ * & 0 \end{bmatrix} \begin{bmatrix} x(t) \\ \eta(t) \end{bmatrix} \tag{9}$$

With (7) and a positive number ε, we know

$$0 \le \begin{bmatrix} x(t) \\ \eta(t) \end{bmatrix}^T \begin{bmatrix} \varepsilon K^T K & 0 \\ * & -\varepsilon I \end{bmatrix} \begin{bmatrix} x(t) \\ \eta(t) \end{bmatrix}$$

By inserting the above formula into (9), we obtain

$$\dot{V}(t) \le \begin{bmatrix} x(t) \\ \eta(t) \end{bmatrix}^T \begin{bmatrix} \overline{A}^T(t)P + P\overline{A}(t) + \varepsilon K^T K & P\overline{B}(t) \\ * & -\varepsilon I \end{bmatrix} \times \begin{bmatrix} x(t) \\ \eta(t) \end{bmatrix}$$

with the condition (8), we know that the system (5) is stable.

Remark2. In theorem1, the control saturation has been transformed to a matrix inequality constraint by using the sector region method, which can effectively deal with the saturation term.

Remark3. Obviously, matrix inequality (8) is not a linear matrix inequality with respect to variables K, P, ε. Next, we will use some matrix transformations to transform the inequality (8) into a linear matrix inequality for variables K, P, ε.

Theorem2. If there are positive matrices $X \in \mathrm{R}^{n\times n}$, matrix $\overline{K} \in R^{m\times n}$, and constants $\overline{\varepsilon} > 0, \varepsilon_1 > 0, \varepsilon_2 > 0$, the following inequality holds

$$\begin{bmatrix} \Xi & \varepsilon^{-1}B & \overline{K}^T & XE_1^T & XE_2^T \\ * & -\overline{\varepsilon}I & 0 & 0 & 0 \\ * & * & -\overline{\varepsilon}I & 0 & 0 \\ * & * & * & -\varepsilon_1 I & 0 \\ * & * & * & * & -\varepsilon_2 I \end{bmatrix} < 0 \tag{10}$$

where

$$\Xi = AX + B\overline{K} + (AX + B\overline{K})^T + \varepsilon_1 D_1 D_1^T + \varepsilon_2 D_2 D_2^T$$

When we design the controller

$$u(t) = 2\overline{K}X^{-1}x(t)$$

the system (5) is stable.

Proof: According to lemma 1, it is easy to know that inequality (8) is equivalent to

$$\begin{bmatrix} \overline{A}^T(t)P + P\overline{A}(t) & P\overline{B}(t) & \varepsilon K^T \\ * & -\varepsilon I & 0 \\ * & * & -\varepsilon I \end{bmatrix} < 0$$

Multiplying both sides of the above equation by matrix $diag\{P^{-1}, \varepsilon^{-1}I, \varepsilon^{-1}I\}$ at the same time, we have

$$\begin{bmatrix} P^{-1}\overline{A}^T(t) + \overline{A}(t)P^{-1} & \varepsilon^{-1}\overline{B}(t) & P^{-1}K^T \\ * & -\varepsilon^{-1}I & 0 \\ * & * & -\varepsilon^{-1}I \end{bmatrix} < 0$$

With (6) and lemma 2, we know that there are constants $\varepsilon_1 > 0$ and $\varepsilon_2 > 0$ make the above inequality is equivalent to

$$\begin{bmatrix} AP^{-1} + BKP^{-1} + (AP^{-1} + BKP^{-1})^T & \varepsilon^{-1}B & P^{-1}K^T \\ * & -\varepsilon^{-1}I & 0 \\ * & * & -\varepsilon^{-1}I \end{bmatrix}$$
$$+\varepsilon_1 \begin{bmatrix} D_1 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} D_1 \\ 0 \\ 0 \end{bmatrix}^T + \varepsilon_1^{-1} \begin{bmatrix} E_1 P^{-1} & 0 & 0 \end{bmatrix}^T \begin{bmatrix} E_1 P^{-1} & 0 & 0 \end{bmatrix}$$
$$+\varepsilon_2 \begin{bmatrix} D_2 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} D_2 \\ 0 \\ 0 \end{bmatrix}^T + \varepsilon_2^{-1} \begin{bmatrix} 0 & \varepsilon^{-1}E_2 & 0 \end{bmatrix}^T \begin{bmatrix} 0 & \varepsilon^{-1}E_2 & 0 \end{bmatrix} < 0$$

By using lemma1 again, the above inequality is equivalent to

$$\begin{bmatrix} \Pi & \varepsilon^{-1}B & P^{-1}K^T & P^{-1}E_1^T & P^{-1}E_2^T \\ * & -\varepsilon^{-1}I & 0 & 0 & 0 \\ * & * & -\varepsilon^{-1}I & 0 & 0 \\ * & * & * & -\varepsilon_1 I & 0 \\ * & * & * & * & -\varepsilon_2 I \end{bmatrix} < 0$$

where

$$\Pi = \varepsilon_1 D_1 D_1^T + \varepsilon_2 D_2 D_2^T + AP^{-1} + BKP^{-1} + (AP^{-1} + BKP^{-1})^T$$

By giving some transforms

$$X = P^{-1}, \overline{K} = KP^{-1}, \overline{\varepsilon} = \varepsilon^{-1}$$

the above inequality is equivalent to (10).

Remark4. By using lemma1 and lemma2, the matrix inequality (10) is linear matrix inequality. And the condition (10) is equivalent to (8). With theorem2, we know that the systems (5) is stable.

IV. Simulation

Example1

Consider the following hybrid model of marine planktonic ecosystem (5)， in order to compare with the PID Algorithm[20], some aspects have to be specified

$$A = \begin{bmatrix} 0.6 & 0 & 0 \\ 0 & -0.2 & 0 \\ 0 & 0 & -0.3 \end{bmatrix}, B = \begin{bmatrix} 0.5 \\ -0.2 \\ 0.1 \end{bmatrix}, D_1 = \begin{bmatrix} 0.01 \\ -0.5 \\ -0.1 \end{bmatrix},$$

$$D_2 = \begin{bmatrix} -0.01 \\ 0.3 \\ 0.1 \end{bmatrix}, F(t) = \sin t, E_1 = \begin{bmatrix} 0.2 & 0.03 & -0.1 \end{bmatrix},$$

$$E_2 = 0.3$$

By using the PID Algorithm, the state feedback controller is obtained

$$u(t) = \begin{bmatrix} 1.4575 & 0.4692 & -3.6202 \end{bmatrix} x(t)$$

On the other, by solving the linear matrix inequality (10), we obtain

$$X = \begin{bmatrix} 1.3426 & 0.3156 & -1.4265 \\ 0.3156 & 0.2356 & 2.1435 \\ -1.4265 & 2.1435 & 3.5626 \end{bmatrix}$$

$$K = \begin{bmatrix} 0.3155 & 1.4266 & -3.4678 \end{bmatrix}$$

$$\bar{\varepsilon} = 0.1345, \varepsilon_1 = 1.6537, \varepsilon_2 = 0.1952$$

the controller can be designed

$$u(t) = \begin{bmatrix} 1.4605 & 0.4063 & -1.4367 \end{bmatrix} x(t)$$

(1) Comparison of the two algorithms

Choosing the initial states as

$$x(0) = \begin{bmatrix} 3 \\ -1 \\ 5 \end{bmatrix}$$

The simulation results of the states $x_1(t), x_2(t), x_3(t)$ are shown in figure 1-3.

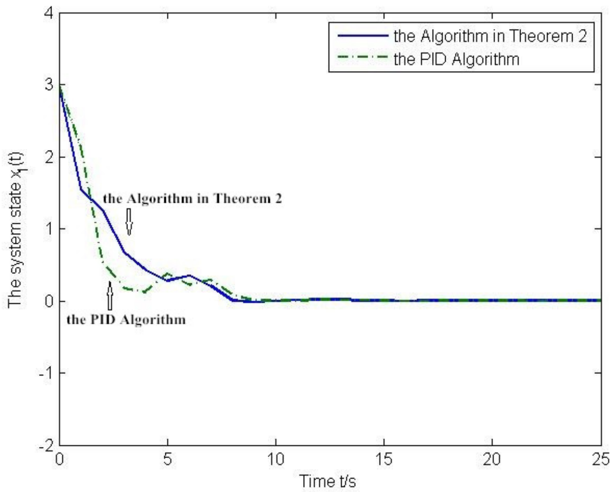

Figure 1. The response curves of $x_1(t)$

The curve of the state $x_1(t)$ obtained by the method presented in this paper has better stability and faster convergence speed, which is smoother than that obtained by PID algorithm.

In figure 2, the results show that the convergence speed of the curve of the state $x_2(t)$ obtained by this method is obviously faster, the overshoot is smaller, and smoother than the state curve obtained by using PID algorithm.

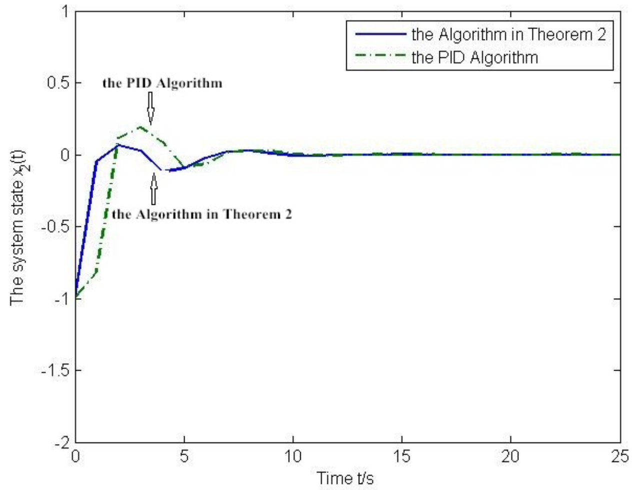

Figure 2. The response curves of $x_2(t)$

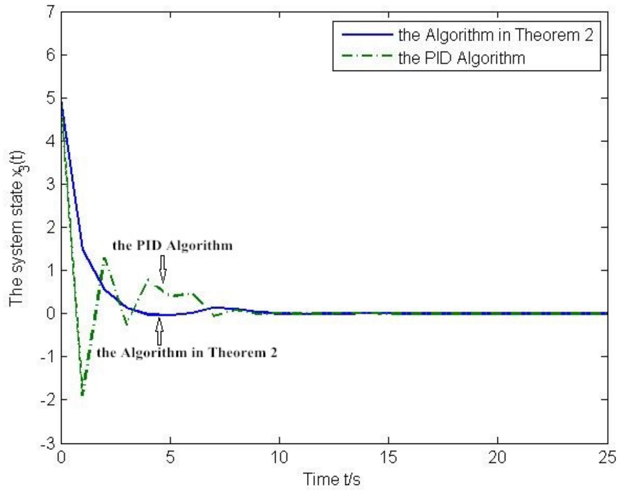

Figure 3. The response curves of $x_3(t)$

The figure3 shows that the convergence speed of the curve of state $x_3(t)$ obtained by the method presented in this paper is obviously faster and the stability is very good, while the state curve obtained by using PID algorithm has obvious oscillation. Therefore, the algorithm in theorem2 presents better results than the PID Algorithm.

(2) Verification of the system performance with the two algorithms

In this paper, we select IAE function to compare the advantages and disadvantages of the two methods. The method with relatively small IAE value is a better method. The form of IAE is as follows

$$IAE = \int_0^\infty |e(t)|\,dt$$

By using the method of this paper and PID method, the value of IAE function is calculated respectively, and the change figure 4 is obtained.

In figure 4, it is easy to see that when the time changes from 0 to 0.2, the IAE values of the two methods are basically equal. However, after 0.2 seconds, the IAE value obtained by PID algorithm is much larger than that of the method proposed in this paper. Therefore, from the IAE value, the method in this paper is due to PID method.

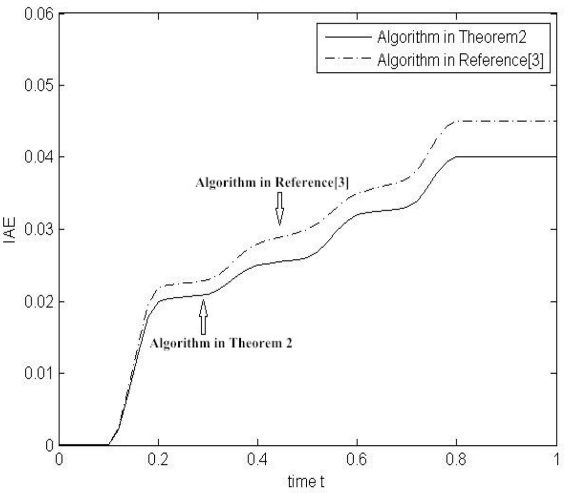

Figure 4. The curves of IAE of the two algorithms

Example2

The design method obtained can be extended to the control process of related control system. In this example, we consider the 1/4 body active suspension system. The equation can be obtained as

$$m_1\ddot{X}_1 = K_1(X_2 - X_1) + b(\dot{X}_2 - \dot{X}_1) + u$$
$$m_2\ddot{X}_2 = -K_1(X_2 - X_1) - b(\dot{X}_2 - \dot{X}_1) + K_2(X_0 - X_2) - u \quad (10)$$

where m_1, m_2 are respectively upper and lower mass of spring, K_1, K_2 are suspension spring stiffness and tire stiffness respectively, b is equivalent suspension damping coefficient, u is the acting force produced by the actuator, X_1, X_2 are vertical displacement of body and suspension respectively, X_0 is the road input.

Selecting vertical displacement X_1 of car body, suspension vertical displacement X_2, vehicle body vertical velocity $\dot{X}_1$ and vertical speed with suspension $\dot{X}_2$ as the state variable x, $x = \begin{bmatrix} X_1 & X_2 & \dot{X}_1 & \dot{X}_2 \end{bmatrix}^T$. Selection of control input vector $u' = \begin{bmatrix} u & X_0 \end{bmatrix}^T$.

$y = \begin{bmatrix} \ddot{X}_1 & \ddot{X}_2 \end{bmatrix}^T$ is selected as the systems output. The state equation can be obtained

$$\dot{x} = Ax + Bu'$$
$$y = Cx + Du'$$

where

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{k_1}{m_1} & \frac{k_1}{m_1} & -\frac{b}{m_1} & \frac{b}{m_1} \\ \frac{k_1}{m_2} & \frac{-k_1 - k_2}{m_2} & \frac{b}{m_2} & -\frac{b}{m_2} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{m_1} & 0 \\ -\frac{1}{m_2} & \frac{k_2}{m_2} \end{bmatrix}$$

$$C = \begin{bmatrix} -\frac{k_1}{m_1} & \frac{k_1}{m_1} & -\frac{b}{m_1} & \frac{b}{m_1} \\ \frac{k_1}{m_2} & \frac{-k_1 - k_2}{m_2} & \frac{b}{m_2} & -\frac{b}{m_2} \end{bmatrix}$$

$$D = \begin{bmatrix} \frac{1}{m_1} & 0 \\ -\frac{1}{m_2} & \frac{K_2}{m_2} \end{bmatrix}$$

The parameters of active suspension are selected as

$$m_1 = 300kg, m_2 = 50kg, k_1 = 20000N/m,$$
$$k_2 = 2000N/m, b = 1800N \cdot s/m$$

With the PID approach, by changing P=-200, -300, -400, the relationship between simulation acceleration and time is shown in Figure 5.

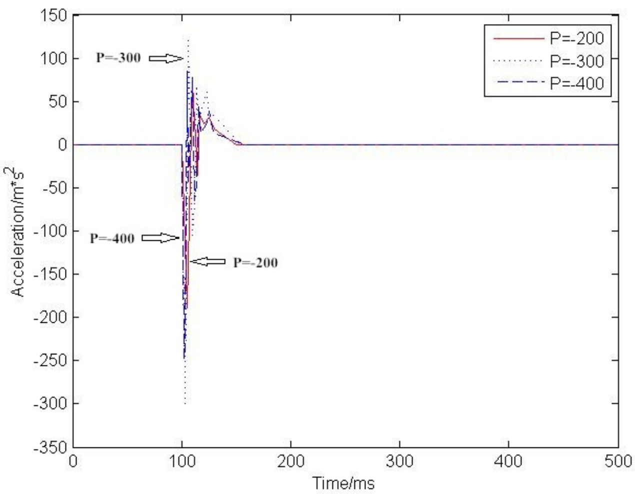

Figure 5. The relation between acceleration and time at different P values

In order to compare with the traditional PID control method, we use the design method given in this paper to design the controller. By solving the linear matrix inequality (10), we obtain the controller as

$$u(t) = [0.2487 \;\; \text{-}1.3450]x(t).$$

By using the two approaches, the relation response curve between acceleration and time is shown in figure 6.

In figure 6, the solid line is the response curve of the algorithm in this paper. The dotted line represents the system state response curve under the action of PID algorithm. It is easy to see from figure 6 that the convergence speed of the solid line is faster than that of the dotted line, and the convergence smoothness is good, and the overshoot is relatively small. The design method given in theorem 2 can effectively improve system performance. Therefore, the algorithm in this paper is superior to PID algorithm.

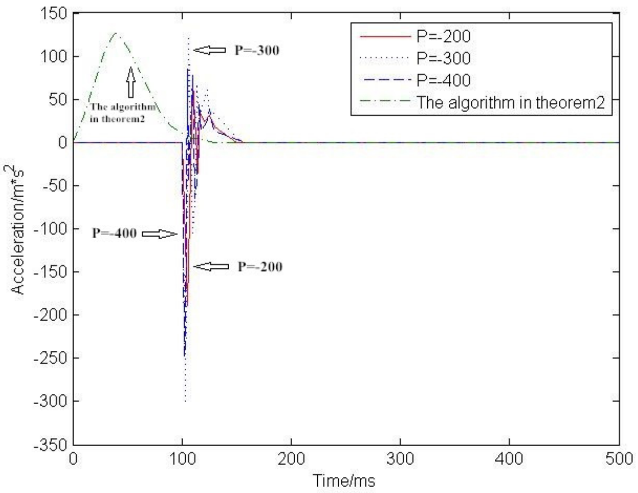

Figure 6. The relation between acceleration and time

Similar to example1, we compare and analyze the system performance through IAE function to compare the systems performance. The IAE functions of the two algorithms are shown in figure 7.

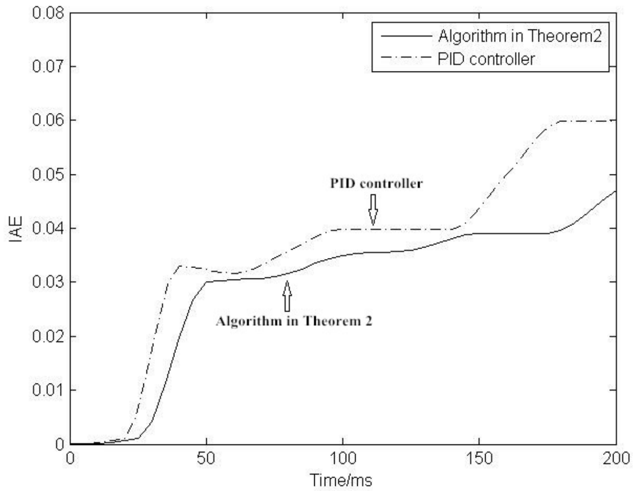

Figure 7. The curves of IAE of the two algorithms

In Figure 7, it is easy to see that when the time changes from 0 to 10, the IAE values of the two algorithms are basically equal. However, after 10 seconds, the IAE value obtained by PID algorithm is much larger than that of the method proposed in this paper. From the IAE value, the algorithm in this paper is obviously better than PID algorithm.

V. Conclusion

In this paper, a new dynamic model of marine plankton ecosystem with saturation is obtained by using logistic model method. Based on the linear matrix inequality approach, the stable condition and the anti-saturation control of the hybrid dynamic model are presented.

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