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Control of Chaotic Behavior in Thruster Motor System for Deepwater Ocean Robot

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Abstract: - In this paper, an adaptive control technique is applied to controlling the chaotic behavior in thruster motor system for deepwater ocean robot. This chaotic oscillation has a direct impact on the stability, reliability and security of the robot. In addition, the proposed approach is also verified in the way of both flexibility and effectiveness, and a kind of chaotic controller that is applicable for manufacturing is designed and constructed. The simulation results show that thruster motor system can escape from the chaotic state in a short time by using the adaptive controller and transfer into continuous stable state. The method presented has an obvious effect on the control.

Key-Word: - Thruster motor, chaos, adaptive control, deepwater robot

1 Introduction

It is interesting to note that sometimes an unexpected drastic vibration occurs in the torque and speed of the thruster motor system for deepwater ocean robot. Due to the limitation of research in learning and analyzing full mechanism for the whole mechanical system while the real system had very irregular behavior, the reason for that problem is generally attributed to external disturbance or system accident. As a matter of fact, in terms of the investigation of modern techniques in nonlinear dynamics, this nonlinear effect is characterized by chaotic behavior.

Ocean robot plays an important role in underwater observation, demarcation and exploration for ocean sources, in which deepwater thruster motor is used as the radical component, whose performance and operation behavior directly affect and determine the dynamic and static performances, reliability and security of the deepwater robot. Therefore, it is necessary to recognize the chaotic operation status of this thruster motor system for deepwater ocean robot and restrain its occurrence so that the thruster motor system can get rid of the chaotic operation status and guarantee that the deepwater works in proper order.

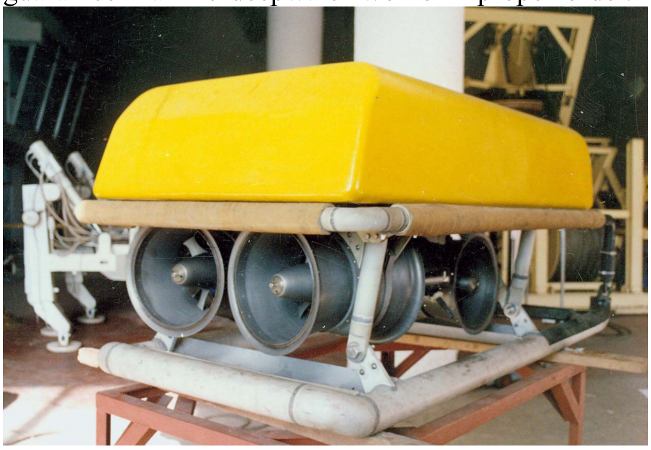

Fig 1 Ocean robot

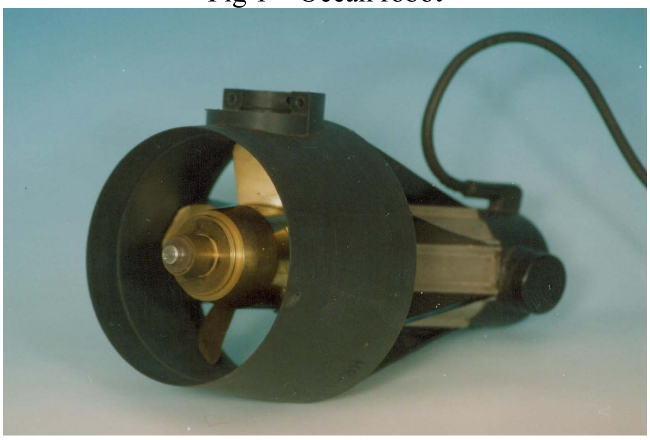

Fig 2 Thruster motor and propeller

Thus, the investigation of chaotic behavior such as Lyapunov exponents etc. is pretty significant in the real world.

2 Chaotic Behavior of Ocean Thruster Motor System

Figure 1 shows an ocean robot equipped with a set of thruster system consisting of multi-thruster motors, which aim at realizing these motions such as moving forwards, moving backwards, floating upwards, diving downwards, turning left, turning right, and various combined movements. The thruster motor and corresponding propeller used in the robot is shown in Figure 2.

In order to discuss theoretically the dynamic chaotic behavior of the thruster motor system for ocean robot, we need to construct the physical model and mathematical model of the dynamic system, respectively. As shown in the literatures [1],[2], [4], [5], [6], after application of coordinate transformation, linear affined transformation and time scaling transformation, the nonlinear chaotic model of the thruster motor system for deepwater robot is expressed as follows:

$$\begin{cases} \dfrac{d\tilde{i}_d}{d\tilde{t}} = \tilde{u}_d - \mu\tilde{i}_d + \tilde{\omega}\tilde{i}_q \\ \dfrac{d\tilde{i}_q}{d\tilde{t}} = \tilde{u}_q - \tilde{i}_q - \tilde{\omega}\tilde{i}_d + \gamma\tilde{\omega} \\ \dfrac{d\tilde{\omega}}{d\tilde{t}} = \sigma\left(\tilde{i}_q - \tilde{\omega}\right) + \nu\tilde{i}_d\tilde{i}_q - \tilde{T}_L \end{cases} \quad (1)$$

where μ , γ , σ and ν are structure parameters of thruster dynamic system; $\tilde{u}_d$ is a voltage on the direct axis, $\tilde{u}_q$ is a voltage on the quadrature axis, $\tilde{T}_L$ is a load torque after transformation; $\tilde{i}_d$ is a current on the direct axis, $\tilde{i}_q$ is a current on the quadrature axis, $\tilde{\omega}$ is a rotation speed after transformation.

Compared with the models of classical Lorenz chaotic system and Chen's chaotic system, it seems that that of thruster motor system looks like them, but, in fact, their topologies are not completely the same. Consequently, the topology complexities of their dynamic system, their dynamic behavior and characteristics are also different.

We can identify chaotic operation properties and characteristics of system through determining the characteristic exponents of nonlinear chaotic system. The general methods for determining the characteristic exponents of nonlinear chaotic system are Lyapunov exponents, power spectrum, Poincaré map and fractal dimension etc. Lyapunov exponents are the most important technique which is employed to define strictly and predict chaos of the system.

Assume that structure parameters of thruster motor system for deepwater ocean studied are given as follows:

$$\mu = 1.00 , \sigma = 5.58 , \quad \gamma = 19.55$$

the initial condition of the system operation is defined as:

$$\begin{bmatrix}\tilde{i}_d & \tilde{i}_q & \tilde{\omega}\end{bmatrix}^T = \begin{bmatrix}0.05 & 0.02 & 0.05\end{bmatrix}^T$$

Lyapunov exponents are calculated respectively under the conditions of the no load sliding, unload operating and load operating of the thruster motor system, which is used to indicate whether or not chaos occurs in the system. The performance curve

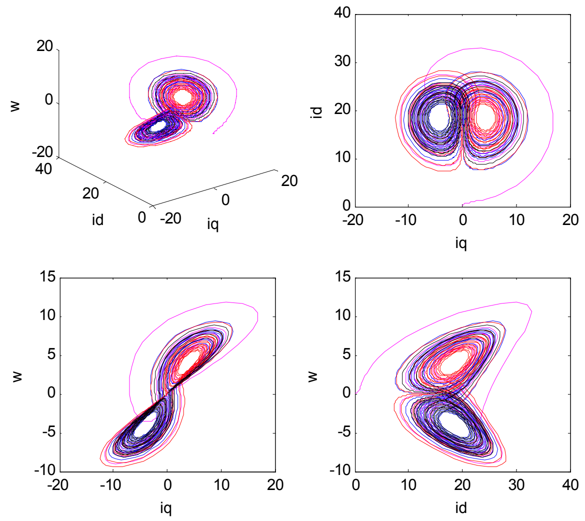

Fig 3 Chaotic attractor of thruster motor system at no load

simulated in case of no load is shown in Figure 3, where the value of coordinate unit is expressed by dimensionless number. Figure 3 clearly illustrates the butterfly effect of attractor of the thruster motor system, which further directly proves that in this case chaotic operation behavior occurs in the thruster motor system.

3 Chaotic Control of Thruster Motor System

In spite of a lot of approaches to eliminating the negative chaotic phenomena involved in systems, we could not resort to only one of methods to restrain all of chaotic phenomena existed in practical engineering since complexities of chaotic systems require the diversity of control methods. For chaotic phenomena existed in the real world, we should take many factors into consideration, like the limitation of initial condition, the flexibility of control measure, and the complexity in design of software and hardware etc. so as to find an appropriate technique according to the concrete problems.

This paper proposed an adaptive control method to restrain the chaotic phenomena of thruster motor system for deepwater robot, this method is simple, reliable and is easy to be achieved. Let us assume that the mathematical model of thruster motor system is represented by following n-order state equation:

$$\dot{\mathbf{x}}(t) = \mathbf{F}(\mathbf{x}(t), \mathbf{u}(t)) \quad (2)$$

by adding a control vector $\mathbf{u}_k$ to the equation (2), the system equation is converted into a disturbance equation of autonomous system, in symbols:

$$\begin{cases}\dot{\mathbf{x}}(t)=\mathbf{F}(\mathbf{x}(t),\mathbf{u}(t))+\mathbf{u}_k \\ \mathbf{u}_k=-K\mathbf{x}(t)\end{cases} \tag{3}$$

Theorem: If we can construct a differentiable positive definite function $V(\mathbf{x})$ and its total derivative $\dot{V}(\mathbf{x})$ calculated along the solution curve of the equation (3) is negative definite, then the undisturbed motion of autonomous system will be asymptotically stable. This theorem is called as Lyapunov asymptotically stable theorem.

Proof: For any small enough ε, we generate a sphere S_ε by setting zero point as a center point and ε as a radius. Then let us assume that l is the minimum of $V(\mathbf{x})$ on the sphere. Since the positive definite function $V(\mathbf{x})$ has infinitesimal upper boundary, we can always find a positive number δ so that any point within the limitation of $\|\mathbf{x}(t)\|\le\delta$ can satisfy the following requirement: $V(\mathbf{x})<l$. Select $\mathbf{x}_0$ as the initial value of $\mathbf{x}(t)$ at $t=t_0$, and meet such form as $\|x_0\|=\|x(t_0)\|\le\delta$, then we have $V(\mathbf{x}_0)<l$. Use the following equation to compute the integration of $\dot{V}(\mathbf{x})$ along solution curve $\mathbf{x}(t)$:

$$V(\mathbf{x})=V(\mathbf{x}_0)+\int_0^t V(\mathbf{x}(t))\mathrm{d}t \tag{4}$$

since $V(\mathbf{x}_0)<l$, $\dot{V}(\mathbf{x})<0$, we have:

$$V(\mathbf{x})\le V(\mathbf{x}_0)<l \tag{5}$$

thus, at any time $t\ge t_0$, the equation $\|\mathbf{x}(t)\|\le\varepsilon$ can be always satisfied. As a result, the undisturbed motion of autonomous system meets the stable requirements.

Through proof by contradiction, it can be proved that $\|\mathbf{x}(t)\|\to 0$ as $t\to\infty$. Provided that there exists a positive number e, when $t\ge t_0$, we have:

$$V(\mathbf{x})>e \tag{6}$$

Similarly, since the positive definite function $V(\mathbf{x})$ has infinitesimal upper boundary, a positive number β must be found so that any point within the limitation of $\|\mathbf{x}(t)\|\le\beta$ can satisfy the following equation: $V(\mathbf{x})<e$.

Consequently, if the equation (6) is true, then the following form must be met:

$$\beta\le\|\mathbf{x}(t)\|\le\varepsilon \tag{7}$$

Let set β as radius to generate a sphere S_β, then solution curve $\mathbf{x}(t)$ must be constrained inside the ring region composed of S_ε and S_β. Let negative definite function $\dot{V}(\mathbf{x})$ have the maximum $-l$ in the closed region, then the estimated value of $V(\mathbf{x})$ in the region can be written as:

$$V(\mathbf{x})=V(\mathbf{x}_0)+\int_0^t V(\mathbf{x}(t))\mathrm{d}t\le V(\mathbf{x}_0)-l(t-t_0) \tag{8}$$

When t is big enough, $V(\mathbf{x})$ turns out to be negative, this conflicts with the condition of positive definitive function $V(\mathbf{x})$. Therefore, equation (6) could not be true. In other words, regardless of small enough e, it is possible for $V(\mathbf{x})<e$ at a certain time $t=t_1$. As $V(\mathbf{x})$ is a decreasing function with time, $V(\mathbf{x})$ will be forever less than e from then on, and tends to be zero gradually; namely, in the case of $t\to\infty$, we have $\|\mathbf{x}(t)\|\to 0$. It is guaranteed that the undisturbed motion of autonomous system will be asymptotically stable. Control strategy is effective.

In terms of Lyapunov asymptotically stable theorem, and the real model and operating condition of the studied system, we need to design a chaotic control algorithm and a kind of chaotic controller to retain the system stable, in other words, it is required to construct a state feedback controller $\mathbf{u}_k$.

In the next section, taking brushless motor for deepwater ocean robot at the condition of no load sliding as an example, state variable $\tilde{i}_d$ is only imposed a control on, and the structure of the controller is configured as $\tilde{u}_{dk}=-k\tilde{i}_d$. Thus, the state equations of controlled brushless motor system can be written as follows:

$$\begin{cases}\dfrac{\mathrm{d}\tilde{i}_d}{\mathrm{d}\tilde{t}}=\tilde{u}_{dk}-\tilde{i}_d+\tilde{\omega}\tilde{i}_q \\ \dfrac{\mathrm{d}\tilde{i}_q}{\mathrm{d}\tilde{t}}=-\tilde{i}_q-\tilde{\omega}\tilde{i}_d+\gamma\tilde{\omega} \\ \dfrac{\mathrm{d}\tilde{\omega}}{\mathrm{d}\tilde{t}}=\sigma(\tilde{i}_q-\tilde{\omega})\end{cases} \tag{9}$$

Lyapunov function is defined as:

$$V=\tilde{i}_d^{\,2}+\tilde{i}_q^{\,2}+\tilde{\omega}^2 \tag{10}$$

then we obtain

$$\begin{aligned}\dot{V}&=2\tilde{i}_d\frac{\mathrm{d}\tilde{i}_d}{\mathrm{d}\tilde{t}}+2\tilde{i}_q\frac{\mathrm{d}\tilde{i}_q}{\mathrm{d}\tilde{t}}+2\tilde{\omega}\frac{\mathrm{d}\tilde{\omega}}{\mathrm{d}\tilde{t}} \\ &=-\begin{bmatrix}\tilde{i}_d & \tilde{i}_q & \tilde{\omega}\end{bmatrix}\begin{bmatrix}-2\sigma & -(\sigma+\gamma) & 0 \\ -(\sigma+\gamma) & 2 & 0 \\ 0 & 0 & 2(1+k)\end{bmatrix}\begin{bmatrix}\tilde{i}_d \\ \tilde{i}_q \\ \tilde{\omega}\end{bmatrix} \\ &=-X^TA(k)X\end{aligned} \tag{11}$$

based on the preceding equation, it is easy to determine feedback gain coefficient k to keep matrix $A(k)$ positive definite, and we obtain

$$\dot{V}=-X^TA(k)X\le-\lambda_{\min}(A(k))\|X\|^2<0 \tag{12}$$

so $V(t)\le V(0)e^{-\lambda_{\min}t}$ (13)

where $\lambda_{\min}$ is the minimum of eigenvalue of $A(k)$.

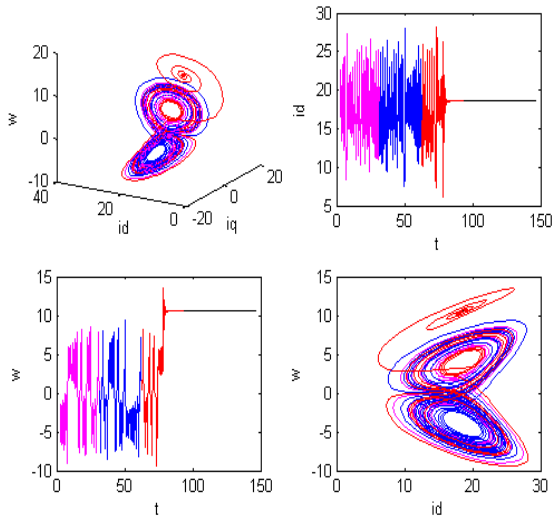

Fig 4 Transient states of chaotic attractor after imposing a control on the system at $t = 78\text{s}$

Since the initial value $V(0)$ of Lyapunov function is bounded, the closed- loop system is unconditionally stable. After being imposed a control, the system will be asymptotically stable at a rate of exponent, and end up with going out the chaotic region.

On the basis of preceding mechanism, we designed and constructed a chaotic adaptive controller to restrain the chaotic behavior of thruster motor system for deepwater ocean robot so that it can quickly jump out of chaotic state and step into the stable domain. Now we set adaptive controller feedback gain coefficient $k = 5.0$, and simulate the thruster motor system controlled and impose this proposed control on it at $t = 78\text{s}$, the simulated results are illustrated in Figure 4, which shows transient states of chaotic attractor.

4 Conclusion

This paper successfully applied modern nonlinear control theory to restraining the chaotic behavior of thruster motor system for deepwater ocean robot. Based on theoretical proof for the feasibility and effectiveness of the proposed method, a chaotic controller is designed and constructed for restraining the chaotic behavior, and the thruster motor system on which a control is imposed is imitated. The results demonstrate that chaotic phenomena existed in the system can be eliminated and it is helpful for getting rids of chaotic region and stepping into continuously stable state. Moreover, the built chaotic controller is with such characteristics as simplicity, effectiveness, and feasibility in engineering processing. It is proved that this technology presented can be used as control strategy and restraint scheme for chaotic operation behavior possibly occurred in the thruster motor system, furthermore, it is helpful for the embedded software development of chaotic control which assures ocean robot works more properly.

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