Research on a New Kind of Robust Backstepping Filter Derivative Control Method

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***Abstract*—A novel Lyapunov function, which contains a concept of transfer function, was constructed to prove the rightness of a new kind of robust backstepping filter derivative control method. Meanwhile, the relationship between Lyapunov function and transfer function was established, which is an important concept that can be applied in a large family of control systems. Also, the backstepping design technology is perfectly integrated with the PID control method, which was testified by the simulation result. And comparing with pure derivative method, better performance was achieved by the adopting of filter derivative method.**

***Index Terms*—Lyapunov function, Transfer function, Filter Derivativel, Backstepping**

I. INTRODUCTION

Transfer function is the most useful and important concept in classic control theory. We have many methods to analysis the stability of transfer functions such as solving the root of polynomial of denominator[1,2]. Lyapunov function is one of the most important tools in modern control theory. It can be used for the design of all kinds of systems, especially for nonlinear complex big systems. It is also a necessary tool to analysis the stability of control system designed with modern control strategies such as adaptive control or backstepping technology or robust control, etc[3-6].Although there is no universal rules to construct a Lyapunov function for a real system, the Lyapunov function method is used widely for the design and analyze of nonlinear systems and most researchers like to use it because it is almost the only effective meant to analyze a complex nonlinear system[7-13]. Also it is a meaningful method because it reveals the relationship between the stability of a system and the virtual energy of a system, so it make the analysis of the stability of a system to be a obvious simple question from the energy point of view sight .

It is obvious that transfer function can be a useful and meaningful part if it can be included in the controller designed with modern control theory. But how to integrate the above two kinds of ideas? And how to analysis the stability of such kind of systems designed with modern control theory and transfer function theory? It is an interesting problem. Some of linear or nonlinear control methods can be explained by the introducing of a Lyapunov function, so it can make those methods easier to be accepted by researchers. Also, it is meaningful to find a Lyapunov function for an accepted old method because we can get more close to the essence of stability of nonlinear systems by thinking this problem from two or more different angles[14-47]. In this paper, the traditional design method, such as PID control and filters, were perfectly integrated with the modern control method such as backstepping technology. And a filter derivative was constructed, which had better performance than pure derivative control according to the numerical simulation at the end of this paper. And the most important part is that the relationship between transfer function and Lyapunov function was revealed by constructing a new type of Lyapunov functions which contains the traditional transfer function.

II. MODEL DESCRIPTION

The following two-order system is taken as an example to illustrate the hybrid control of backstepping and integral approach.

$$\begin{aligned} \dot{x}_1 &= f_1(x_1) + \Delta f_1(x) + x_2 \\ \dot{x}_2 &= f_2(x) + \Delta f_2(x) + u \end{aligned} \tag{1}$$

Assumption 1: there exists known constants c_{i0} and c_{i1} such that $\left|\Delta f_i(x) - \dot{x}_i^d\right| \le c_{i0} + c_{i1}\left|z_i\right|$.

III. DESIGN OF CONTROLLER WITH PURE DERIVATIVE METHOD

Define a new variable as $z_1 = x_1 - x_1^d$, then the first order subsystem can be written as

$$\dot{z}_1 = f_1(x_1) + \Delta f_1(x) + x_2 - \dot{x}_1^d \tag{2}$$

Design a virtual control as

$$\begin{aligned} x_2^d &= -f_1(x_1) - k_{P1}z_1 - k_{D1}\dot{z}_1 - k_{I1}\int z_1 dt \\ &\quad - k_{s1}sign(z_1) - k_{t1}\frac{z_1}{\left|z_1\right| + \varepsilon_1} \end{aligned} \tag{3}$$

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Define a new variable as $z_2 = x_2 - x_2^d$, then the following equation holds

$$(1+k_{D1})z_1\dot{z}_1 + k_{I1}z_1\int z_1 dt = z_1\left(\Delta f_1(x) - \dot{x}_1^d\right) + z_1 z_2 - k_{P1}z_1^2 - k_{s1}|z_1| - k_{t1}\frac{z_1^2}{|z_1|+\varepsilon_1} \quad (4)$$

Considering the second subsystem, we have

$$\dot{z}_2 = f_2(x) + \Delta f_2(x) + u - \dot{x}_2^d \quad (5)$$

Design the control as

$$u = -f_2(x) - z_1 - k_{P2}z_2 - k_{D2}\dot{z}_2 - k_{I2}\int z_2 dt - k_{s2}sign(z_2) - k_{t2}\frac{z_2}{|z_2|+\varepsilon_1} \quad (6)$$

So the equation can be arranged as

$$(1+k_{D2})z_2\dot{z}_2 + k_{I2}z_2\int z_2 dt = z_2\left(\Delta f_2(x) - \dot{x}_2^d\right) - z_1 z_2 - k_{P2}z_2^2 - k_{s2}|z_2| - k_{t2}\frac{z_2^2}{|z_2|+\varepsilon_2} \quad (7)$$

Choose the Lyapunov function as

$$V = \frac{1}{2}\sum_{i=1}^{2}(1+k_{Di})z_i^2 + k_{Ii}(\int z_i dt)^2 \quad (8)$$

Solve the derivative of the Lyapunov function and get

$$\dot{V} = \sum_{i=1}^{2} z_i\left(\Delta f_i(x) - \dot{x}_i^d\right) - k_{Pi}z_i^2 - k_{si}|z_i| - k_{ti}\frac{z_i^2}{|z_i|+\varepsilon_i} \quad (9)$$

According to the assumption, there exist parameters k_{Pi} and k_{si} which is big enough such that

$$\dot{V} \le 0 \quad (10)$$

Now, it is easy to prove that the system is stable.

IV. Example and Simulation

Considering the above two-order system, we choose

$$\begin{aligned} f_1(x_1) &= 3x_1, \Delta f_1(x) = \sin(x_1 x_2) + x_1 \\ f_2(x) &= 4x_2, \Delta f_2(x) = x_2\cos(x_1 x_2) \end{aligned} \quad (11)$$

Then the two order system can be written as

$$\begin{aligned} \dot{x}_1 &= 3x_1 + \sin(x_1 x_2) + x_1 + x_2 \\ \dot{x}_2 &= 4x_2 + x_2\cos(x_1 x_2) + u \end{aligned} \quad (12)$$

We define the desired signal as $x_1^d = 5$ set the control parameters as $k_{P1} = 5$, $k_{Ii} = k_{si} = k_{ti} = 5$, $k_{P2} = 20$, and do the simulation with parameter as $k_{D1} = 0$ and $k_{D1} = 1$ respectively, the simulation result can be shown as Fig.1 and Fig. 2. We can know from the above figures that the overshoot can be reduced by adopting the backstepping and PD hybrid control method, also the performance of the system can be improved. But we should also point out that if the derivative coefficient does not increase properly, oscillation will be caused (For example, we choose $k_{D1} = k_{D2} = 1$ to do the simulation and the bad performance can be shown as Fig 3) or the system will become unstable (For example, we choose $k_{D1} = 2, k_{D2} = 1$ to do the simulation and the bad performance can be shown as Fig.4). Also, in some situation, the demand for simulation algorithm will become very strict if the pure derivative item is used. In other hand, it is very difficult to get some derivative signals in many actual systems, so we will consider adopting a filter derivative to take place the pure derivative.

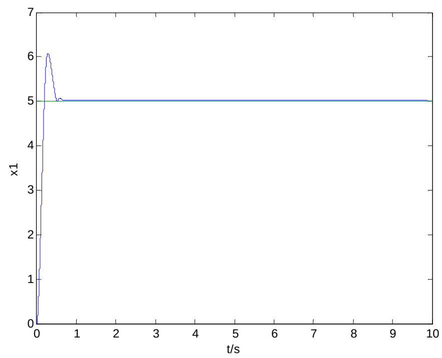

Figure 1. Curve of x1($k_{D1} = 0$)

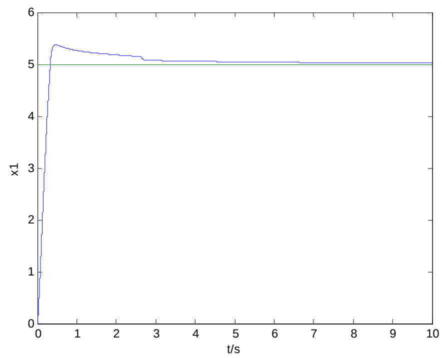

Figure 2. Curve of x1 ($k_{D1} = 1$)

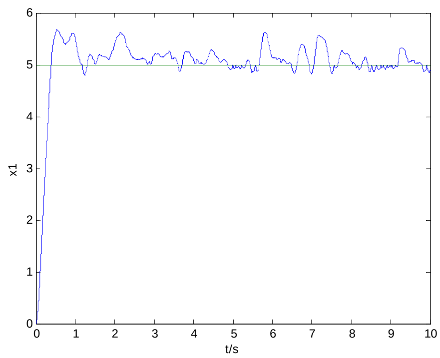

Figure 3. Curve of x1 ($k_{D1} = k_{D2} = 1$)

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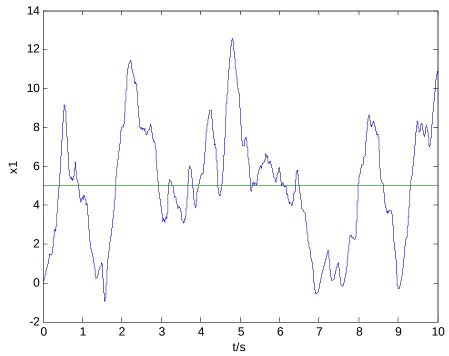

Figure 4. Curve of x1($k_{D1}=2, k_{D2}=1$)

V. PROOF OF FILTER DERIVATIVE METHOD

Considering the above system

$$\begin{aligned}\dot{x}_1 &= f_1(x_1)+\Delta f_1(x)+x_2 \\ \dot{x}_2 &= f_2(x)+\Delta f_2(x)+u\end{aligned} \quad (13)$$

We define $z_1 = x_1 - x_1^d$ and the first subsystem can be written as

$$\dot{z}_1 = f_1(x_1)+\Delta f_1(x)+x_2-\dot{x}_1^d \quad (14)$$

Design a virtual control as

$$\begin{aligned}x_2^d &= -f_1(x_1)-k_{P1}z_1-k_{D1}\frac{s}{\tau_1 s+1}z_1 \\ &-k_{I1}\int z_1 dt - k_{s1}sign(z_1)-k_{t1}\frac{z_1}{|z_1|+\varepsilon_1}\end{aligned} \quad (15)$$

where $\frac{s}{\tau_1 s+1}$ is a filter which is used to get an approximate derivative of the error

$$L=\frac{1}{2}\frac{z^2}{\tau s+1}=\frac{J}{\tau s+1}\geq 0, J=\frac{1}{2}z^2 \quad (16)$$

Then we have $\tau\dot{L}+L=J$ and solve the derivative we get

$$\begin{aligned}\dot{L} &= \frac{1}{\tau}J-\frac{1}{\tau}V=\frac{1}{\tau}\frac{1}{2}z^2-\frac{1}{\tau}\frac{z^2}{\tau s+1} \\ &= \frac{1}{2}\frac{1}{\tau}z\left[z-\frac{z}{\tau s+1}\right]=\frac{1}{2}z\left[\frac{sz}{\tau s+1}\right]\end{aligned} \quad (17)$$

Design $z_2 = x_2 - x_2^d$ then the following equation holds

$$\begin{aligned}&z_1\dot{z}_1+k_{I1}z_1\int z_1 dt+\left(\frac{1}{2}\frac{k_{D1}z_1^2}{\tau_1 s+1}\right)' \\ &= z_1\left(\Delta f_1(x)-\dot{x}_1^d\right)+z_1 z_2-k_{P1}z_1^2-k_{s1}|z_1|-k_{t1}\frac{z_1^2}{|z_1|+\varepsilon_1}\end{aligned} \quad (18)$$

Considering the second subsystem

$$\dot{z}_2 = f_2(x)+\Delta f_2(x)+u-\dot{x}_2^d \quad (19)$$

We design the control as

$$\begin{aligned}u &= -f_2(x)-z_1-k_{P2}z_2-k_{D2}\frac{s}{\tau_1 s+1}z_2 \\ &-k_{I2}\int z_2 dt-k_{s2}sign(z_2)-k_{t2}\frac{z_2}{|z_2|+\varepsilon_1}\end{aligned} \quad (20)$$

Then the system can be arranged as

$$\begin{aligned}&z_2\dot{z}_2+k_{I2}z_2\int z_2 dt+\left(\frac{1}{2}\frac{k_{D2}z_2^{\ 2}}{\tau_2 s+1}\right)' \\ &= z_2\left(\Delta f_2(x)-\dot{x}_2^d\right)-z_1 z_2-k_{P2}z_2^2-k_{s2}|z_2|-k_{t2}\frac{z_2^2}{|z_2|+\varepsilon_2}\end{aligned} \quad (21)$$

And the Lyapunov function can be chosen as

$$V=\frac{1}{2}\sum_{i=1}^{2}\left(z_i^2+k_{Ii}\left(\int z_i dt\right)^2+k_{Di}\frac{z_i^{\ 2}}{\tau_i s+1}\right) \quad (22)$$

The derivative of Lyapunov function can be computed as

$$\dot{V}=\sum_{i=1}^{2}z_i\left(\Delta f_i(x)-\dot{x}_i^d\right)-k_{Pi}z_i^2-k_{si}|z_i|-k_{ti}\frac{z_i^2}{|z_i|+\varepsilon_i} \quad (23)$$

According to the assumption, there exist two big enough parameters k_{Pi} and k_{si} such that

$$\dot{V}\leq 0 \quad (24)$$

So it is easy to prove that the system is stable.

VI. EXAMPLE AND SIMULATION

Now the above system is used to do the simulation and we set

$$\begin{aligned}f_1(x_1)&=3x_1, \Delta f_1(x)=\sin(x_1 x_2)+x_1 \\ f_2(x)&=4x_2, \Delta f_2(x)=x_2\cos(x_1 x_2)\end{aligned} \quad (25)$$

then the second order system can be written as

$$\begin{aligned}\dot{x}_1 &= 3x_1+\sin(x_1 x_2)+x_1+x_2 \\ \dot{x}_2 &= 4x_2+x_2\cos(x_1 x_2)+u\end{aligned} \quad (26)$$

Define the desired value as $x_1^d=5$ and use the backstepping and filter derivative hybrid control method, and choose the control parameters as $k_{P1}=5$, $k_{Ii}=5$, $k_{si}=k_{ti}=5$, $k_{P2}=20$, $k_{D1}=2,\ \tau_1=0.001$ and $k_{D2}=1, \tau_2=0.1$. The simulation result can be shown as Fig.5. If we use the pure derivative but not the filter derivative, the system is unstable even though the same coefficient for derivative is used. The comparison means that the filter derivative can better

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improve the performance of the system compared with pure derivative method.

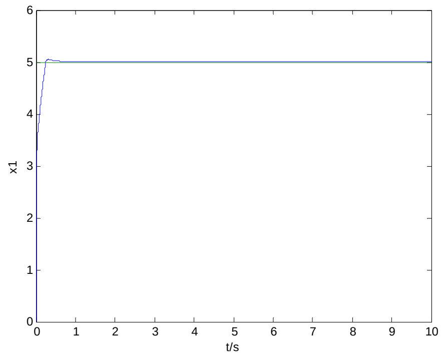

Figure 5. Curve of x1

Considering that we further increase the uncertainties of the system, we choose $\Delta f_2(x) = x_2 \cos(x_1 x_2) x_1^2$ and use pure derivative to do the simulation. Through a series of

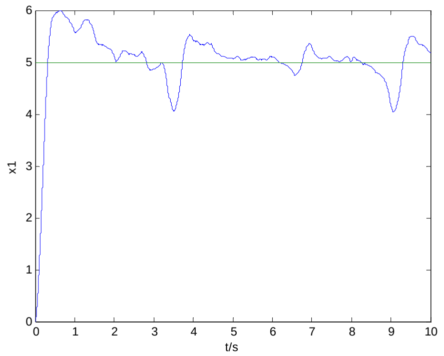

Figure 6. Curve of x1

simulations, we found a better one with parameters as $k_{D1} = 0.5, k_{D2} = 1$, and the simulation result can be shown as Fig 6. It is obvious that if we want to reduce the oscillation and make the curve smooth, we need to increase the derivative coefficients. But the increase of the derivative caused the system to be unstable unexpectedly, which can be shown as Fig 7 where the

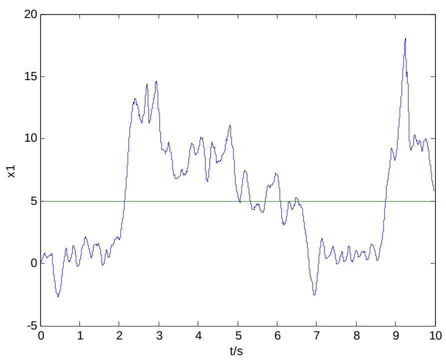

Figure 7. Curve of x1

parameters are chosen as $k_{D1} = 2, k_{D2} = 1$.

Later, used the filter derivative algorithm and chose parameters as $k_{D1} = 2, \tau_1 = 0.001$, $k_{D2} = 1, \tau_2 = 0.1$, the control effect is not very good, which can be shown as Fig 8. And we changed the parameters as

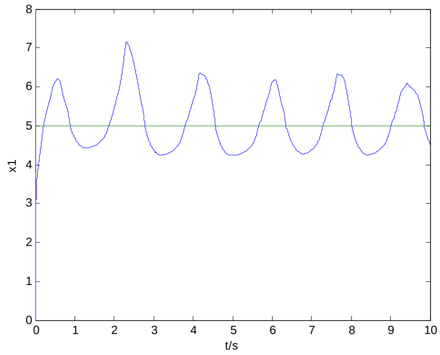

Figure 8. Curve of x1

$k_{D1} = 5, \tau_1 = 0.001$ and $k_{D2} = 3, \tau_2 = 0.1$, and the simulation result can be shown as Fig9. Also, the

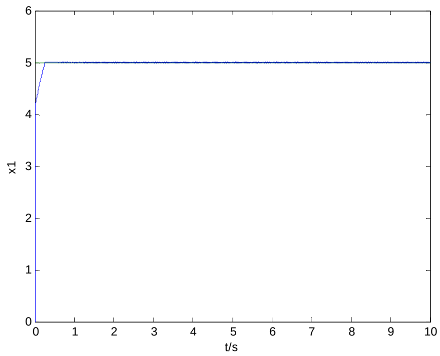

Figure 9. Curve of x1

parameters can be chosen in a big interval, and the possibility that the system become unstable is reduced.

After that, when consider the situation that the input is limited, and assume the saturation value of input is 2500, then the response speed is slow and overshoot and oscillation are appeared as Fig 10. That is because of the uncertainties of the system and meanwhile the energy of the input is limited. Further, we increase the uncertainty of the system and choose $\Delta f_2(x) = x_2 \cos(x_1 x_2) x_1^2 + x_2^2$, and then the system is unstable. And this problem can not be solved by simply increasing the coefficient of integral item or derivative item. Another reason is that the assumption of this paper does not satisfied, so it is an important part of our future work.

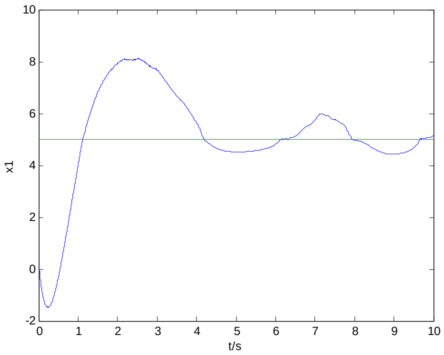

Figure 10. Curve of x1

VII. CONCLUSIONS

Above of all, the main contribution of this paper can be concluded as following points. First, a novel type of filter derivative method was introduced to robust backstepping design. Second, the relationship between transfer function (an important concept in classic control theory) and Lyapunov function (one of the most popular concept in modern control theory) was established. What is very different from other papers is that detailed and elaborate simulations were done in this paper to research the problem that how much uncertainties and how big an amplitude of uncertainties can be solved by this filter derivative method.

At last, the paper also shows some situations that the proposed new method can not cope with and the reasons are given to explain the result. Also, it points out our future research field.

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