Journal of Marine Science and Technology

Volume 24 | Issue 1 Article 7

ANTI-WINDUP SCHEMES FOR NONLINEAR ACTIVE DISTURBANCE REJECTION CONTROL IN MARINE STEAM TURBINE

Yuan-Qing Wang
Marine Engineering College, Dalian Maritime University, Dalian, China

Guang Ren
Marine Engineering College, Dalian Maritime University, Dalian, China.

Jun-Dong Zhang
Marine Engineering College, Dalian Maritime University, Dalian, China., zhjundong@163.com

Recommended Citation
Wang, Yuan-Qing; Ren, Guang; and Zhang, Jun-Dong (2016) "ANTI-WINDUP SCHEMES FOR NONLINEAR ACTIVE DISTURBANCE REJECTION CONTROL IN MARINE STEAM TURBINE," *Journal of Marine Science and Technology*: Vol. 24: Iss. 1, Article 7.
DOI: 10.6119/JMST-016-0125-7
Available at: https://jmstt.ntou.edu.tw/journal/vol24/iss1/7

ANTI-WINDUP SCHEMES FOR NONLINEAR ACTIVE DISTURBANCE REJECTION CONTROL IN MARINE STEAM TURBINE

Acknowledgements

This work is supported by National Natural Science Foundation (NNSF) of China under Grant 51479017, the Specialized Fund for the Basic Research Operating expenses Program of Central College 3132015337.

Journal of Marine Science and Technology, Vol. 24, No. 1, pp. 47-53 (2016)
DOI: 10.6119/JMST-016-0125-7

ANTI-WINDUP SCHEMES FOR NONLINEAR ACTIVE DISTURBANCE REJECTION CONTROL IN MARINE STEAM TURBINE

Yuan-Qing Wang[1], Guang Ren[1], and Jun-Dong Zhang[1]

Key words: steam turbine, active disturbance rejection control, anti-windup, control.

ABSTRACT

Nonlinear characteristics are very common in marine steam turbine, such as control input constraints and external disturbances. Based on the active disturbance rejection control (ADRC), an anti-windup scheme is proposed to eliminate the undesired effects of nonlinear characteristics in the control system. In this scheme, firstly, a method of setting parameter is designed for nonlinear active disturbance rejection control (NLADRC). Then, two kinds of anti-windup schemes are proposed in this paper for NLADRC in the presence of control input constraints and external disturbances. Finally, simulation study is carried out for a first order delay object with actuator constraints, simulation results show that both schemes can achieve good anti-windup performance. The method is further extended to marine steam turbine control, with simulation results demonstrating that both methods have their own advantages.

I. INTRODUCTION

Because of the work stability and large output power, steam turbine was widely used in aircraft carrier, destroyer and LNG Carrier. But the steam turbine also presents nonlinear characteristics such as external disturbances and control input constraints, which inevitably requires the system to adjust the time variable length, overshoot, delay and oscillation problems. Therefore, a straightforward and feasible approach to avoid these drawbacks is still an urgent task, which challenges the design of controller. The traditional PI control was improved by Wang Shuangxin, who designed a fuzzy PI control system (Wang et al., 2005). Lei Shixiong designed the steam turbine speed fuzzy PID control system, to achieve the speed of the turbine speed tracking, and meet the stability control requirements (Lei et al., 2009). The above control methods improve the performance of the steam turbine control dramatically, however, the problem of the input constraints has not yet to be considered and solved.

Anti-windup control is divided into a direct design method and a compensation method (Kothare, 1997; Zhou and Tan, 2014).

The direct design method is the control input of the actuator directly into the controller design. Model predictive control is a typical direct design method (Maciejowski, 2002), with each sampling period added to the control input constraint. Therefore, it is believed to be the most effective way to deal with the input saturation. But the related algorithm is complex since it depends heavily on the constraint information. With variations of constraints, the control algorithm needs to be recalculated.

Anti-windup compensation principle is briefly described as follows: when nominal systems are affected by large external disturbances, control input saturation is reached. Meanwhile, deviation signal will appear in control inputs and outputs of the actuator. Through the design of the anti-windup compensator, the adverse effects of the deviation signal are eliminated. Anti-windup theory is widely applied in industry, however, when it comes to the designing with more efficient compensation link, further systematical study becomes necessary and urgent (Tong et al., 2010; Wu and Lin, 2010, 2012; Yu et al., 2015).

Active disturbance rejection control is a nonlinear control method proposed by Professor Han Jingqing. It inherits the advantages of classic PID control algorithm, which adopted the error feedback control system instead of depending on the model; at the same time, it combines the modern control theory and the extended state observer (ESO) method, being able to estimate and compensate disturbances (internal and external ones), to overcome the contradictions of traditional PID speed and accuracy. Anti-windup compensation method that used in linear active disturbance rejection control (Zhou and Tan, 2014), improves the control effect when the turbine control input becomes saturated. However, as the control object is a nonlinear system, the control effect is limited; Futhermore, lag control exists when using the anti-windup compensation method, thus overshoot control is easily to appear.

It is well known that the nonlinear active disturbance rejection control (NLADRC) is better than the linear controller (Lei and Lu, 2000; Sun, et al., 2007). Therefore, the method of

Paper submitted 10/22/15; revised 11/13/15; accepted 01/25/16. Author for correspondence: Jun-Dong Zhang (e-mail: zhjundong@163.com).
[1] Marine Engineering College, Dalian Maritime University, Dalian, China.

NLADRC is used in this paper. Meanwhile, the improved anti-windup compensation methods were designed based on the delayed and anticipatory anti-windup control method of NLADRC. Finally, the control method is applied to the marine steam turbine, and the effectiveness of the present method is verified by simulation experiments. The performance of delay anti-saturation method of NLADRC meets the requirements, with low energy consumption, fast control speed of anticipatory anti-windup control method, and small overshoot.

II. NONLINEAR ACTIVE DISTURBANCE REJECTION CONTROL (NLADRC)

NLADRC does not need an accurate model of the controlled object and disturbances. Generally, the plant model normally used is,

$$x^{(n)} = f(x, ..., x^{(n-1)}, t) + w(t) + bu(t) \tag{1}$$

where $f(x, ..., x^{(n-1)}, t)$ is the unknown dynamics in the system, $w(t)$ is the external disturbance, $u(t)$ is the input in the system control, b and n are two known variables.

For $x_1 = x(t)$, $x_2 = x^{'}(t)$, …, $x_n = x^{(n-1)}(t)$, system in (1) becomes:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 \\ \vdots \\ \dot{x}_n = f(x_1, x_2, ..., x_n) + w(t) + bu(t) \end{cases} \tag{2}$$

For $a(t) = f(x_1, x_2, ..., x_n) + w(t)$, we usually take the unknown part of the system and the external disturbance as the generalized perturbations.

For system (2), it can be constructed as the formula (3) non-linear ESO, each state variable of the system (3) can track each state variable of the system (2).

$$\begin{cases} \dot{z}_1 = z_2 - h_1(z_1 - x(t)) \\ \dot{z}_2 = z_3 - h_2(z_1 - x(t)) \\ \vdots \\ \dot{z}_n = z_{n+1} - h_n(z_1 - x(t)) + bu(t) \\ \dot{z}_{n+1} = -h_{n+1}(z_1 - x(t)) \end{cases} \tag{3}$$

For $x_n = x^{(n-1)}(t)$, $\delta x_1 = z_1 - x_1$, $\delta x_2 = z_2 - x_2$, …, $\delta x_n = z_n - x_n$, $\delta x_{n+1} = z_{n+1} - a(t)$, formula (3)-(2) becomes (4).

$$\begin{cases} \delta x_1 = \delta x_2 - h_1\delta x_1 \\ \delta x_2 = \delta x_3 - h_2\delta x_1 \\ \vdots \\ \delta x_n = \delta x_n - h_n\delta x_1 \\ \delta x_{n+1} = -h_{n+1}\delta x_1 - a^{'}(t) \end{cases} \tag{4}$$

where $a^{'}(t)$ is the derivative of $a(t)$.

Hypothesis $a^{'}(t)$ have bound conditions, order:

$$A = \begin{vmatrix} -h_1 & 1 & 0 & \cdots & 0 \\ -h_2 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -h_n & 0 & 0 & \cdots & 1 \\ -h_{n+1} & 0 & 0 & \cdots & 0 \end{vmatrix}, \quad E = \begin{vmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ -1 \end{vmatrix}$$

$$\delta X = (\delta x_1, ..., \delta x_n)^T,$$

The system (4) can then be expressed as

$$\delta X = A\delta X + Ea^{'}(t) \tag{5}$$

where

$$a^{'}(t) = \frac{\partial a(t)}{\partial \delta x_1}\delta x_1 + \frac{\partial a(t)}{\partial \delta x_2}\delta x_2 + \frac{\partial a(t)}{\partial \delta x_n}\delta x_n + \frac{\partial a(t)}{\partial \delta x_{n+1}}\delta x_{n+1},$$

so

$$\delta X = \begin{vmatrix} -h_1 & 1 & 0 & \cdots & 0 \\ -h_2 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -h_n & 0 & 0 & \cdots & 1 \\ -h_{n+1} - \frac{\partial a(t)}{\partial \delta x_1} & -\frac{\partial a(t)}{\partial \delta x_2} & -\frac{\partial a(t)}{\partial \delta x_3} & \cdots & -\frac{\partial a(t)}{\partial \delta x_{n+1}} \end{vmatrix} \delta X$$

$$= A^{'}\delta X \tag{6}$$

If values of parameters h_1, h_2, …, h_{n+1} can make the characteristic root of $A^{'}$ in the left half plane of the complex plane, and the real part is negative, system (6) would be asymptotically stable at the origin. Thus, each state variable of system (3) tracks each state variable of system (2) and general disturbance $a(t)$.

Because the system is uncertain, $\frac{\partial a(t)}{\partial \delta x_1}$, …, $\frac{\partial a(t)}{\partial \delta x_{n+1}}$ is unknown in matrix $A^{'}$, so it cannot be directly based on the eigenvalues of the matrix in the left half plane of the complex plane, and the real part is full negative, to make the system stable condition to determine the value of h_1, h_2, …, h_{n+1}. The tuning method of the parameter h_1, h_2, …, h_{n+1} is as follows:

1) At system (5), suppose desirable characteristic roots are l_1, l_2, …, l_{n+1}, then the value of the parameter h_1, h_2, …, h_{n+1} should satisfy: $|sI - A| = \prod_{i=1}^{n+1}(s - l_i)$.

To make each system of the polynomials on s at two sides of the above formula respectively equal, the value of the parameter h_1, h_2, …, h_{n+1} can be obtained.

2) Parameter h_1, h_2, …, h_{n+1} are brought into formula (3), and the simulation system (1) is carried out. If the state variables of formula (3) are able to track the state variables of system (2) and $a(t)$, at this point, the value of h_1, h_2, …, h_{n+1} becomes the final value. Otherwise, reselecting the expected pole values l_1, l_2, …, l_{n+1} of matrix A in formula (5), then repeating steps 1) and 2).

As long as the system (5) is configured properly, the characteristics of the system (6) are in the left half plane of the complex plane and the real part of full negative, thus the system (6) is asymptotically stable at the origin. We are able to use z_{n+1} to estimate the value of generalized perturbed $a(t)$ in real time, even though the $f(x_1, x_2, ..., x_n)$ and the $w(t)$ of the system are unknown and time-depending, which is

$$z_1 \to x(t), ..., z_n \to x^{(n-1)}(t), z_{n+1} \to x^{(n)}(t) = a(t) \quad (7)$$

Taking the following control law:

$$U(t) = \frac{1}{b}(u_0(t) - z_{n+1}(t)) \quad (8)$$

The formula (6) and (7) into the system (2) may be:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 \\ \vdots \\ \dot{x}_n = u_0(t) \end{cases} \quad (9)$$

The feedback control law can be used in this system,

$$u_0(t) = k_1(r(t) - x(t)) + k_2(\dot{r}(t) - \dot{x}(t)) + ... + k_n(r^{(n-1)}(t) - x^{(n-1)}(t)) \quad (10)$$

where $r(t)$ as a reference signal to be tracked, because z_1, …, z_n approach to $x(t)$, …, $x^{(n-1)}(t)$, therefore, the formula (10) can be written as

$$U(t) = \frac{k_1(r(t) - x(t)) + ... + k_n(r^{(n-1)}(t) - x^{(n-1)}(t))}{b} - \frac{z_{n+1}(t)}{b} = K(\hat{r}(t) - \hat{z}(t)) \quad (11)$$

where $\hat{r}(t)$ is a generalized reference signal,

$$\hat{r}(t) = [r(t)\ \hat{r}(t) \ ...\ r^{(n-1)}]^T$$

State feedback gain K:

$$K = [k_1\ k_2\ ...\ k_n]/\mathrm{b} \quad (12)$$

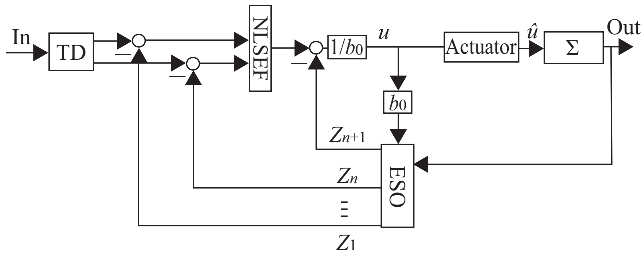

Fig. 1. Structure of NLADRC.

In summary, the structure of the NLADRC is shown in Fig. 1, where TD is the over-process, NLSEF is the nonlinear feedback, ESO is the extended observer, "actuator" refers to the actuator while Σ refers to the control object.

Therefore, the control equation of the NLADRC is determined,

$$\begin{cases} \dot{z}_1 = z_2 - h_1(z_1 - x(t)) \\ \vdots \\ \dot{z}_n = z_{n+1} - h_n(z_1 - x(t)) + bu(t) \\ \dot{z}_{n+1} = -h_{n+1}(z_1 - x(t)) \\ u(t) = K(\hat{r}(t) - \hat{z}(t)) \end{cases} \quad (13)$$

The NLADRC required a tuning parameter of h_1, h_2, …, h_{n+1} and K. The first group can be completed as the preceding 1), 2), and the parameters K can be completed by using the method proposed by Zhou and Tan (2014).

III. ANTI-WINDUP DESIGN OF NLADRC

Because ADRC algorithm has not considered the problem involved in the control input saturation, the control performance would be deteriorated when the actuator is constrained. Therefore, it is very important to solve the problem related to the control input saturation of ADRC. In this regard, numerous researches have been done at home and abroad recently. During which, the main method is the design of anti-windup compensators that compensating the saturation control signal. For example, this idea is applied by Zhou and Tan (2014). based on which the delayed and anticipatory anti-windup algorithm is designed.

In Fig. 2, the delayed anti-windup is designed for NLADRC, where $\bar{u}$ is the first saturation function, which is artificially set and the saturation is higher than $\hat{u}$, which is the second saturation function, i.e., the control input saturation. When the system is saturated, the anti-windup compensator stops working immediately, the effect of the saturation is overcome by the robustness of the system itself.

As shown in Fig. 2, the delayed anti-windup structure has the following state space realization, where $\bar{u}$ is a human set

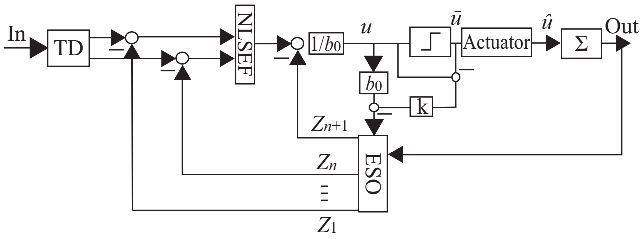

Fig. 2. The architecture of delayed anti-windup scheme of NLADRC.

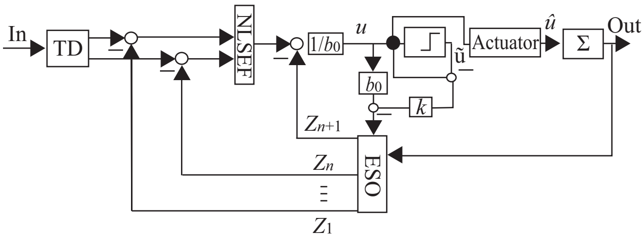

Fig. 3. The architecture of anticipatory anti-windup scheme of LADRC.

$$\begin{cases} \dot{z}_1 = z_2 - h_1(z_1 - x(t)) \\ \vdots \\ \dot{z}_n = z_{n+1} - h_n(z_1 - x(t)) + bu(t) - k(u - \bar{u}) \\ \dot{z}_{n+1} = -h_{n+1}(z_1 - x(t)) \\ u(t) = K(\hat{r}(t) - \hat{z}(t)) \end{cases} \tag{14}$$

of saturation function,saturation is greater than the saturation $\hat{u}$ of the actuator. K is the feedback coefficient. The greater the value, the more powerful the feedback, while the excessive value would lead to system fluctuations.

Fig. 3 is the anticipatory anti-windup scheme. $\tilde{u}$ is a set value, which is less than the saturation $\hat{u}$ of the system. Therefore, the anti-windup module keeps working before the control system reaches saturation.

As shown in Fig. 3, the anticipatory anti-windup has the following state space realization,

$$\begin{cases} \dot{z}_1 = z_2 - h_1(z_1 - x(t)) \\ \vdots \\ \dot{z}_n = z_{n+1} - h_n(z_1 - x(t)) + bu(t) - k(u - \tilde{u}) \\ \dot{z}_{n+1} = -h_{n+1}(z_1 - x(t)) \\ u(t) = K(\hat{r}(t) - \hat{z}(t)) \end{cases} \tag{15}$$

where $\tilde{u}$ is set to be the saturation function. Saturation is less than the saturation $\hat{u}$ of the actuator.

Example 1, the following is a first order delay object

$$G_P(s) = \frac{1}{s+1} e^{-0.2s} \tag{16}$$

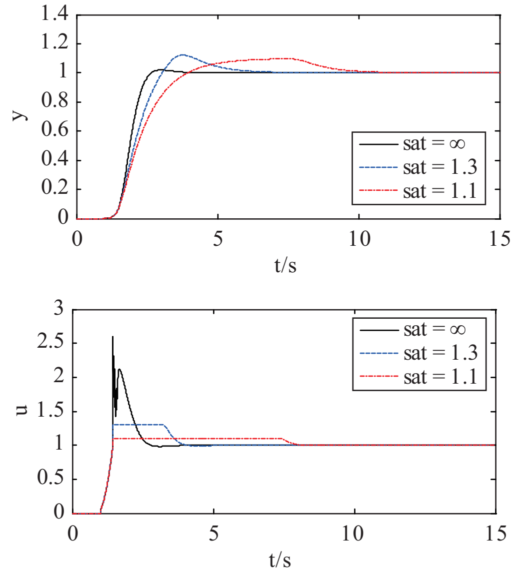

Fig. 4. Step responses of the closed-loop system under NLADRC with actuator: without anti-windup.

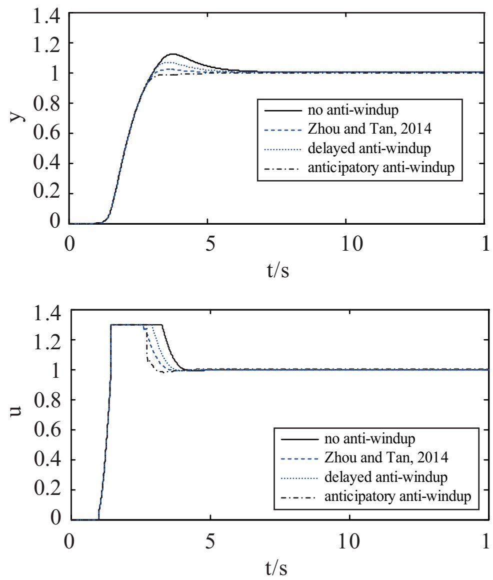

Fig. 5. Step responses of the system with anti-windup at sat = 1.3.

Actuator dynamic is:

$$G_a(s) = \frac{1}{0.2s+1} e^{-0.1s} \tag{17}$$

Anti-windup control is carried out with the three order nonlinear ADRC. Where, $h_1 = 2,\ h_2 = 500,\ h_3 = -200,\ k_1 = 400,\ k_2 = 100$.

In order to verify the performance of the NLADRC properties, the step reference signal is added when t = 1s, and the presence of the actuator is limited. The simulation results are shown in Fig. 4 and Fig. 5.

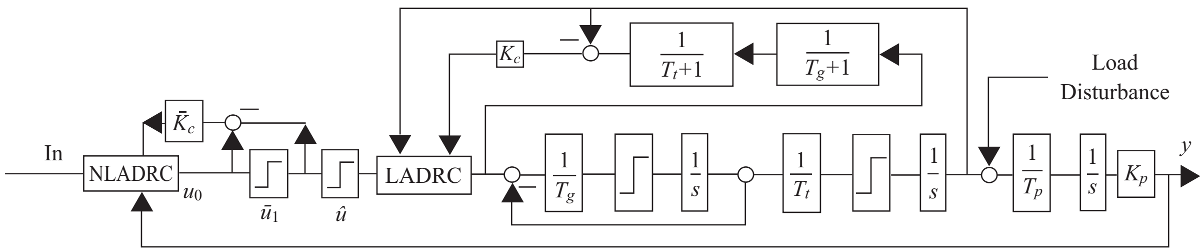

Fig. 6 The architecture of delayed anti-windup scheme.

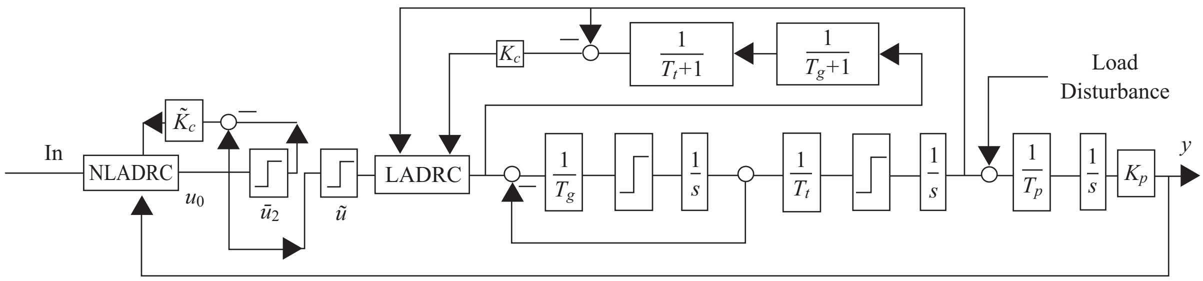

Fig. 7 The architecture of anticipatory anti-windup scheme.

It is concluded from Fig. 4 that:

1) Either "In the absence of actuator limit" or "In the case when there is no actuator limit", NLADRC is fast and the fluctuation is small.

2) In the presence of actuator limits, the larger the limit, the greater the system fluctuates.

Fig. 5 is the actuator output limit sat = 1.3, different anti-windup methods of simulation were considered, which include no anti-saturation treatment, the anti-windup method for LADRC (Zhou and Tan, 2014), delayed anti saturation method, anticipatory anti-saturation method. As shown in Fig. 5, it is obvious that:

1) Anticipatory anti-saturation effect is the best and the fastest, with the smallest fluctuations.

2) The effect of delayed anti-saturation is worse than the anti-saturation method for LADRC (Zhou and Tan, 2014), but better than the method of without anti-saturation. Secondly, according to the actual situation of human set $\bar{u}$ saturation value, when the control object is running in condition with a small disturbance, the general actuator saturation will be smaller. By the regulation of $\bar{u}$, controller anti-windup device would not act or stay with a small action, which largely reduces the system energy consumption.

Besides, Fig. 4 and Fig. 5 also confirmed the feasibility of NLADRC parameter tuning method.

IV. APPLICATION IN STEAM TURBINE CONTROL

In order to guarantee the life and safety of a turbine rotor, the speed control system should be controlled strictly. Recently, the NLADRC control has been used in steam turbine (Zhou and Tan, 2014), and the improvement method for the compensation was proposed (Yang and Chen, 2015). In this paper, we further study the saturation control of NLADRC.

Marine steam turbine control system mainly includes control valve, steam turbine, load and rotor, etc. (Wang et al., 2014). Specially,

control valve: $\dfrac{1}{T_g s+1}$

steam turbine: $\dfrac{1}{T_t s+1}$

load and rotor: $\dfrac{K_p}{T_p s+1}$

In an actual system, there are many nonlinear characteristics, such as the limiting amplitude, speed limit, dead time, time delay and so on, which reduce the control performance of the system. Considering these characteristics, we designed the following two anti-windup schemes for ADRC, with principle given in Fig. 6 and Fig. 7.

Based on the multi-constraint features of the steam turbine, each constraint is set to be a separate anti-windup program, then the system will become complicated, causing the instability of the system. Therefore, the control object ontology multi constraint handling is as follows: The actual output and the theory of output error are the external disturbances, combined with linear ADRC for saturation compensation. As long as the compensation parameter K_C is reasonable, the saturation characteristic of the object itself can be handled (Zhou and Tan, 2014).

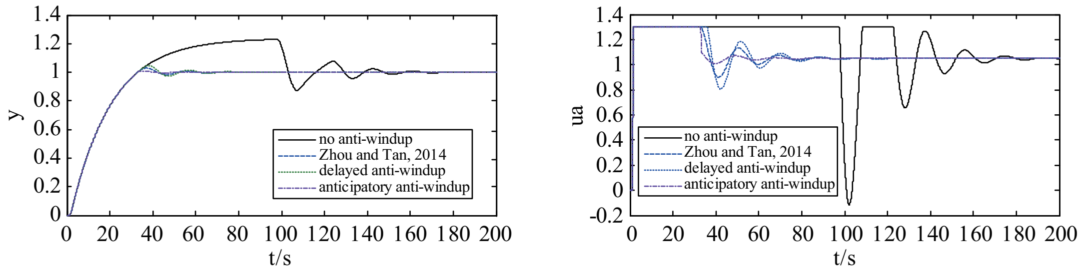

Fig. 8. Step responses of the Steam Turbine system under NLADRC with actuator saturation: with anti-windup at sat = 1.3.

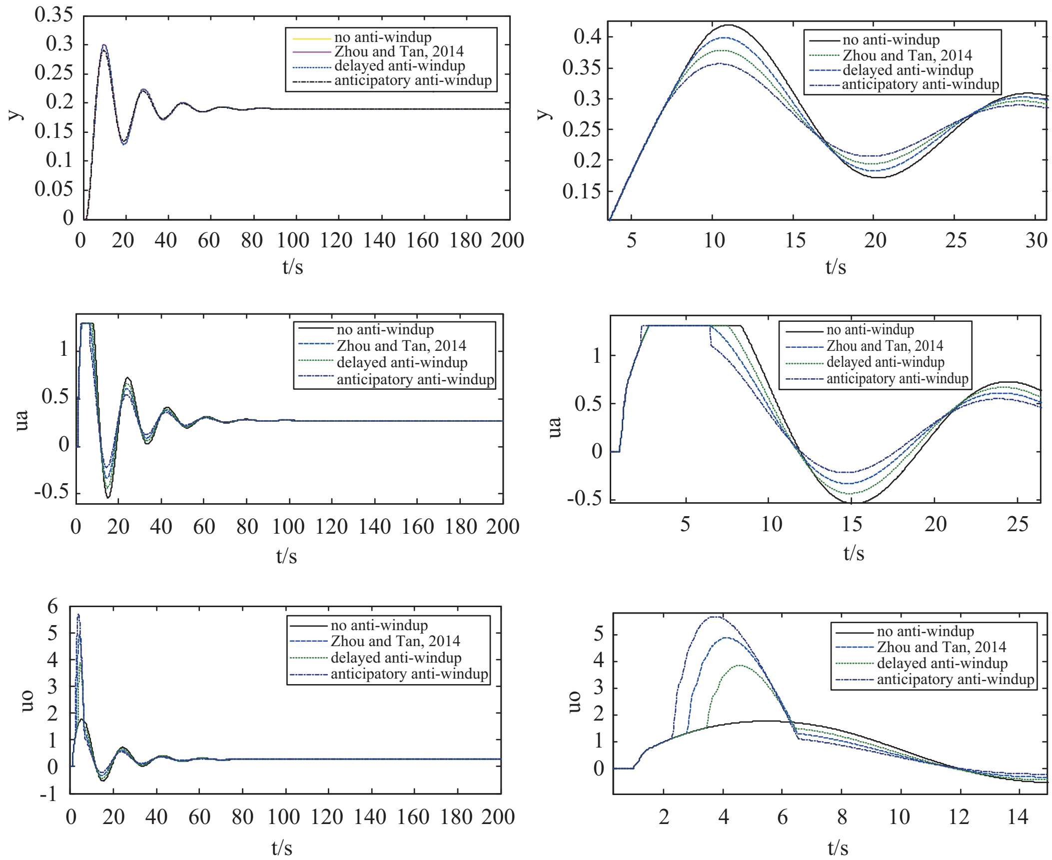

Fig. 9. The architecture of the Steam Turbine system under NLADRC with anti-windup at sat = 1.3.

For the actuator control input constraints, because of its saturation can be accurately measured or instructed, such as Figs. 6 and 7, this paper uses the delayed and anticipatory anti-windup for NLADRC. Finally, the control of the cascade saturation control is formed. To simplify the naming, the delayed anti-windup scheme and anticipatory anti-windup scheme were introduced.

For the delayed anti-windup scheme, as shown in Fig. 6, the artificially saturation $\overline{u}_1$ is higher than the actuator saturation $\hat{u}$. If the actuator is just saturated, the anti-saturation system does not work, and robustness of the control system itself may overcome the saturation state at this time, to reduce the controller is the number of operations, energy consumption is small. And in the anticipatory anti-windup, as given in Fig. 7, the saturation of $\overline{u}_2$ is smaller than that of the actuator saturation, so the anticipatory anti-windup work quickly when system entering saturation state, which makes the system move faster, and can quickly overcome the negative effect of the saturation of the system.

In the end, effect of the method is verified by simulation experiments.

V. SIMULATION EXPERIMENT

Consider the following model of the ship turbine system with $T_t = 0.3$, $T_g = 0.08$, $T_p = 6.2$, $K_P = 120$. In this paper, we use three orders nonlinear ADRC to control, and the method of determining the parameters is shown in the second section. Where, $h_1 = 6$, $h_2 = 300$, $h_3 = -300$, $k_1 = 500$, $k_2 = 200$. In the two kinds of anti-saturation schemes, $K_C = 0.4$, $\bar{K}_C = 0.35$, $\tilde{K}_C = 0.35$. The linear ADRC parameters for the two schemes are $b = 200$, $\omega_c = 3.5$, $\omega_o = 20$.

As shown in Fig. 8, the value of y for the anticipatory anti-windup scheme fluctuation is the smallest. The value ua is the $\tilde{u}$ given in Fig. 7, with smallest fluctuation as well. On the contract, there is a large fluctuation in the system without the use of anti-windup scheme. But delayed anti-windup scheme is worse than the results described in previous literature (Zhou and Tan, 2014). The possible reason might be that after the saturation compensation, the partial saturation is compensated, leading to the system fluctuation. Fig. 9 is the step input with in = 0.25, the perturbation is smaller than the unit step. At this point, the effect of anticipatory anti-windup scheme is the best. However, in all these three methods of anti-windup, the initial input value u_0 of delayed anti-windup scheme is the minimum. This is meaningful to the practical control system because in the small degree of saturation, by applying the present approach, the control effect can be improved, which will meet the system requirement, minimum the energy consumption, and reduce the operating costs of the system.

VI. DISCUSSION AND CONCLUSIONS

In this paper, the delayed and anticipatory anti-windup control methods of NLADRC are proposed for the multi-constraint characteristics of steam turbine. It was found out by the simulations results that, the control speed of anticipatory anti-windup scheme becomes much faster in response, with a slighter system fluctuations and overshoot. When the system runs stably, and external perturbation is small, the initial input value u_0 of delayed anti-windup scheme is the minimum. Moreover, this approach can improve the control effect and reduce the operating costs of the system.

ACKNOWLEDGMENTS

This work is supported by National Natural Science Foundation (NNSF) of China under Grant 51479017, the Specialized Fund for the Basic Research Operating expenses Program of Central College 3132015337.

REFERENCES

Kothare, M.V. (1997). Control of systems subject to constraints. Los Angeles: California Institute of Technology.

Lei, S.X. (2009). Fuzzy control system of turbine speed. Ship Electronic Engineering 29(8), 48-50.

Lei, Z.M. and Z.D. Lu (2000). Nonlinear auto-disturbance rejection controller for spacecraft attitude control system spacecraft attitude control system. Aerospace Control 4(1), 34-39.

Maciejowski, J.M. (2002). Predictive control with constraints. England: Prentice Hall.

Sun, K., L.P. Huang and Y. Mei (2007). A nonlinear auto-disturbance rejection control for matrix converter fed induction motor drive system. Transactions of China Electro technical Society 22(12), 39-45.

Tong, S., X. He and Y. Li (2010). Adaptive fuzzy back stepping robust control for uncertain nonlinear systems based on small-gain approach. Fuzzy Sets and Systems 161(6), 771-796.

Wang, S. X., Y. S. Wang and H. J. Zhu (2005). Research on fuzzy control of turbine regulating system. Journal of System Simulation 17(9), 2196-2198.

Wang, Y. H., J. J. Gu, X. Y. Zhang and B. X. Yuan (2014). Research on speed controller in marine nuclear steam turbine based on cascade feed for ward-feedback fuzzy PID algorithm. Ship Engineering 36(1), 66-70.

Wu, X. and Z. Lin (2010). Anti-windup in anticipation of actuator saturation. IEEE Conference on Decision and Control (CDC). Atlanta, IEEE: 5245-5250.

Wu, X. and Z. Lin (2012). On immediate, delayed and anticipatory activation of anti-windup mechanism: static anti-windup case. IEEE Transactions on Automatic Control 57(3), 771-777.

Yang, Q.Y. and M. Chen (2015). Robust control for near space vehicles with input saturation. Control Theory & Applications 32(1), 19-28.

Yu, M., W. G. Yu and J. Cheng (2015). The influencing factors of populated islands' typhoons and its defensive countermeasures research. Journal of coastal research, Special Issue 73, 348-352.

Zhou, H. and W. Tan (2014). Anti-windup schemes for linear active disturbance rejection control. Control Theory & Ap plications 31(11), 1457-1463.