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The New Design Strategy on PID Controllers

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1. Introduction

PID control is a classical control technique. Because of its simplicity and robustness, it is still extensively used in the control of many dynamical processes. The dominative status of PID control in engineering applications is unchanged even with the advances of modern control theories. However, owing to the uncertainty or complexity of the controlled systems, and the randomness of the external disturbances, PID control still faces a great challenge. How to design an effective PID controller as well as with simple architecture? To meet the requirements for the control of practical systems, a breakthrough should be made in the design strategy of PID controllers.

In this chapter, a brief summing-up will be made on the basic ideas which have been considered in the tuning of PID controllers. It is also intended to provide a summary on the new design strategy of PID controllers, which has been proposed in recent decades. It will be emphasized that the further improvements to the design method will be based on the advance of modern control theory rather than just based on a certain technique.

The chapter is organized as follows: In section 2, some of the conventional methods which have been extensively used on the tuning of PID controllers will be discussed. In section 3, it will be reviewed on the breakthrough made for PID controller designing, especially in China in recent years. It includes three aspects: Firstly, it is the method of signal processing by using tracking-differentiators (TDs), which is fundamental for improving PID control; Secondly, it is the nonlinear PID controller, which uses nonlinear characteristics to improve the performance of PID control; Thirdly, it is the method of active disturbance rejection control (ADRC) which can reject the uncertainties and disturbances by using an extended state observer (ESO), and can implement the output regulation effectively. In section 4, the new separation principle on PID controller tuning is discussed, in which the design of disturbance rejection and the design of effective output regulation can be carried out separately, and disturbances can be rejected without using any observer. Therefore it makes the design of PID controllers more effective and simple. And another new method based on the stripping principle is also discussed, which is an extension of the new separation principle to networked control systems. In section 5, some applications are provided to indicate the efficiency of the methods discussed in section 4. Followed by some conclusions.

2. A brief summary on the conventional methods of PID controller tuning

As been pointed out above, PID control is still being widely used in process control because of its robustness and with relatively simple structure, thousands of books and papers have been published (see (Åström & Hagglund, 1995), (Cong & Liang, 2009), (Datta et al., 2000), (Han, 2009), (Heertjes et al., 2009), (Hernandez-Gomez et al., 2010), (Leva et al., 2010), (Nusret & Atherton, 2006), (Santibanez et al., 2010), (Yaniv & Nagurka, 2004), etc.). However, the main problem in PID control is how to tune the parameters to adapt the controller to different situations ((Han, 2009), (Leva et al., 2010), (Liu & Hsu, 2010), (Sekara et al., 2009), (Toscano & Lyonnet, 2009)). In this section, the conventional methods on the tuning of PID controllers will be summarized.

2.1 The conventional PID control and the requirements

Classical PID control is an implementation of error-based feedback control. The basic principle is particularly rather primitive and simplified. It can be described by the following formula.

Suppose that $y_r(t)$ is the set output or reference input, and $y(t)$ is the actual output of the system. Then the error is $e(t) = y(t) - y_r(t)$, and the classical PID control input is the one as follows:

$$u(t) = -a_0 \int_{t_0}^{t} e(\tau)d\tau - a_1 e(t) - a_2 \dot{e}(t) \tag{1}$$

where a_0, a_1, and a_2 are the design parameters or the gains of integral, proportional, and derivative, respectively.

Before going into the discussion on conventional tuning methods, let's look at what are the purposes of the controller tuning. If possible, it would like to have both of the following for the control system:

- Fast responses, and
- Good stability (the overshoot should be limited to a certain extent).

Unfortunately, for most practical processes being controlled with a PID controller, these two criteria can not be achieved simultaneously ((Han, 1994), (Han, 2009), (Haugen, 2010)). In other words, the result will be

- The faster responses, the worse stability, or
- The better stability, the slower responses.

For a practical control system, it often shows that the output response will sway due to a step change of the setpoint.

And in most cases, it is important that having good stability is better than being fast. So, the acceptable stability (good stability, but not so good, as it gives too slow of a response) should be specified. That is to say, a way of trade-off between fastness and overshoot should be found ((Han, 1994), (Han, 2009)).

From the viewpoint of practical implementations, the most important of all is that the structure of the controller should be as simple as possible.

2.2 The tuning methods based on the knowledge of systems

There are a large number of tuning methods, but for covering most practical cases, there are three kinds of methods for calculating proper values of PID parameters, i.e. controller tuning. These methods are as follows ((Haugen, 2010)):

• The good gain method

It is a simple experimental method which can be used without any knowledge about the process to be controlled. It aims at obtaining acceptable stability as explained above. The method is a simple one which has proven to give good results on laboratory processes and on simulators.

However, if a process model can be obtained, the good gain method can be used on a simulator instead of in the physical process.

• Skogestad's method

It is a model-based tuning method. It is assumed that the mathematical model (a transfer function) of the process can be obtained. It does not matter how to derive the transfer function - it can stem from a model derived from physical principles, or from the calculation of model parameters (e.g. gain, time-constant and time-delay, etc.) from an experimental response, typically a step response experiment with the process.

With this tuning method, the controller parameters should be expressed as functions of the process model parameters.

• Ziegler-Nichols' methods

It is the ultimate gain method (or closed-loop method) and the process reaction curve method (the open-loop method).

The ultimate gain method has actually many similarities with the good gain method, but the former method has one serious drawback. Namely, it requires the control loop to be brought to the limit of stability during the tuning, while the good gain method requires a stable loop during the tuning. The Ziegler-Nichols' open-loop method is similar to a special case of Skogestad's method, and Skogestad's method is more applicable.

2.3 The methods based on improving the control performance

From another point of view, or according to the attention paid to improving control performance ((Åström & Hagglund, 2004), (Heertjes et al., 2009) ,(Sekara et al., 2009)), the tuning methods can be summarized as follows.

Firstly, the intelligent methods, such as neural networks, fuzzy theory, particle swarm optimization, etc., have been employed to tune the PID controllers, and some rules have been obtained by technical analysis and a series of experiments. The rules based on certain logical relationships are popularly used, especially with the applications of computer technology.

Secondly, the separation method of PID controller tuning was proposed ((Åström & Hagglund, 1995)). The parameters can be determined based on features of the step response, for example, K, T_i, T_d and T_f are determined to deal with disturbances and robustness, and the parameters b and c can then be chosen to give the desired set-point response. However, the trouble with the method is that the tuning for disturbance rejection and for robustness are mixed, so there are some difficulties for choosing the parameters.

Thirdly, the appearance of integration method, the main trends are that the effectiveness of most tuning methods is enhanced by the combination of PID control with other control methods such as, variable structure control, artificial neural networks, intelligent control, etc., see (Cong & Liang, 2009), (Haj-Ali & Ying, 2004), (Li & Xu, 2010), (Liu & Hsu, 2010).

In spite of the improvements on the tuning methods mentioned above, most of them are still empirical. The trouble with the existing PID control methods is that the more requirements, the more complicated the structure and more parameters to be tuned ((Han, 2009), (Oliveira et al., 2009), (Sekara et al., 2009)).

3. The new improvements to conventional PID controllers

In this section, some new efforts which have been made in recent decades will be reviewed. They are the proposition and development of a group of methods relevant with the improvement of PID control. Because they have essential effects on the tuning of PID controllers, they will be discussed with more details.

3.1 The nonlinear tracking-differentiators

As it is known, the implementation of PID controllers needs to obtain the derivative of the error between the actual output and reference input. Unfortunately, the errors often contain measurement noise, or are usually in discrete form. That is to say, they are discontinuous, let alone differentiable. Usually, people use the difference to replace the derivative. It may amplify the affects of noise, and result in worse control results.

At the same time, the reference input or the setpoint being encountered may also be nondifferentiable, i.e., perhaps the tracked patterns are unusual ones, such as square waves, sawtooth waves, etc.

To avoid setpoint jump, it is necessary to construct a transient profile which the output of the plant can reasonably follow. While this need is mostly ignored in any typical control textbook, engineers have devised different motion profiles in servo systems.

To overcome these drawbacks, or to meet these needs for implementing PID control, and to obtain the derivatives of signals which are nondifferentiable, or contain noise, the nonlinear tracking-differentiator (TD) was introduced. And the general forms and theoretical results of TDs can be found in (Han & Wang, 1994). One of the specific forms of TDs is a nonlinear system as follows:

$$\begin{cases} \dot{y}_1 = y_2 \\ \dot{y}_2 = -R_1 sat\left(y_1 - y_r(t) + \frac{|y_2|y_2}{2R_1}, \delta\right) \end{cases} \tag{2}$$

where *sat* is the saturation function. From (Han & Wang, 1994), it is proved that, as $R_1 \to \infty$, the following equality holds,

$$\lim_{R_1 \to \infty} \int_0^T |y_1(t) - y(t)| dt = 0 \tag{3}$$

That is to say, $y_1 \to y_r$ as $R_1 \to \infty$. So, y_2 can be regarded as the (generalized) derivative of y_r. It can be used as the derivative for PID control.

At the same time, higher-order derivatives can be obtained by using cascading of TDs, and the transient process can also be arranged by using TDs to overcome overshoots in the responses of PID control, especially for the set inputs which are nondifferentiable.

And because TDs use integrators to process the signal, they also have the ability to filer the noise, especially for dealing with measurement noise.

3.2 The nonlinear PID controllers

Usually, conventional PID control, as a control law, employs a linear combination of proportional (present), integral (accumulative), and derivative (predictive) forms of the tracking error. And, for a long time, other possibilities of combinations, which may be much more effective, are ignored. As a result, it often needs the method on trade-off between overshoot and fastness of the control response.

On the other hand, based on the inspiration of intelligent control, the response curve of neural networks is often a S-type curve, i.e. it is nonlinear. And the optimal control also uses feedback with nonlinear form. Can the control performance be improved by using certain kinds of nonlinear error feedback?

In order to avoid the contradiction between overshoot and fastness in output response of conventional PID controllers, the nonlinear PID (NPID) controller was introduced (see (Han, 1994) and the references therein). Then the control input can be chosen as follows:

$$u(t) = -a_0 \left| \int_{t_0}^{t} e(\tau)d\tau \right|^{\alpha} sgn\left(\int_{t_0}^{t} e(\tau)d\tau\right) - a_1|e(t)|^{\alpha} sgn(e(t)) - a_2|\dot{e}(t)|^{\alpha} sgn(\dot{e}(t)) \tag{4}$$

where $0 < \alpha \leq 1$ is also a design parameter. It has been proved that, the proper choice of α can improve the damping ability for overshoot ((Han, 1994), (Han, 1995)). As to the nonlinear forms in (4), the general expression for these functions is selected heuristically based on experimental results, such as the following one,

$$g(e_1,\alpha,\delta) = \begin{cases} |e_1|^{\alpha} sgn(e_1), & as \ \ |e_1| > \delta, \\ \frac{e_1}{\delta^{1-\alpha}}, & as \ \ |e_1| \leq \delta \end{cases} \tag{5}$$

An important property of the function $g(\cdot,\cdot,\cdot)$ is that, for $0 < \alpha < 1$, it yields a relatively high gain when the error is small, and a small gain when the error is large. The constant δ is a small number used to limit the gain in the neighborhood of the origin and defines the range of the error corresponding to high gain ((Han, 1998), (Talole et al., 2009)).

At the same time, the nonlinear feedback usually provides surprisingly better results to the output response in practice. For example, with linear feedback, the tracking error, at best, approaches zero in infinite time; Otherwise, with nonlinear feedback of the following form

$$u = |e|^{\alpha} sgn(e)$$

where $\alpha < 1$, the error can reach zero much more quickly. Such α can also help reduce steady state error significantly, to the extent that an integral control, together with its downfalls, can be avoided. In the extreme case, $\alpha = 0$, i.e., bang-bang control, the nonlinear feedback can bring the system with zero steady state error, even if without the integral term in PID control. It is because of such efficacy and unique characteristics of nonlinear feedback that people proposed a systematic and experimental investigation. There are also some nonlinear feedback functions, such as fal and $fhan$, which play an important role in the newly proposed control framework ((Han, 1998), (Han, 2009)).

Furthermore, by using the tracking-differentiator (TD) in the nonlinear PID controller, the following needs can be satisfied, for example, to deal with measurement noise and to make a powerful tracking for targets which are nondifferentiable or even discontinuous, such as sawtooth wave, square wave, or even certain random signals, etc.

The trouble in the nonlinear PID controller is how to find the proper parameters when dealing with different situations.

3.3 Active disturbance rejection control

With the advances mentioned above, another improvement to PID control technique is the proposition of active disturbance rejection control (ADRC) ((Han, 1998), (Han, 2009)), which inherited the essence from conventional PID controllers and observers. The basic principle of ADRC is that it uses the extended state observer (ESO) ((Han, 1995), (Talole et al., 2009)) to estimate the total disturbances and uncertainties, and then it forces the system to change in a canonical way. Then it only needs to construct a control input for the canonical system.

3.3.1 The extended state observer (ESO)

One of the main troubles in system synthesis is the uncertainties and disturbances. How to find an effective way to deal with these factors? One of the reasonable methods is to construct an estimator.

In order to do that, it is necessary to introduce a new concept: total disturbance, i.e. in a system which contains uncertainties and disturbance, all the nonlinear parts including uncertainties and disturbance, and even the external noise can be regarded as a whole of the total disturbance. Although such a concept is, in general, applicable to most nonlinear multi-input-multi-output (MIMO) time varying systems, for the sake of simplicity and clarity, only a second-order single-input-single-output (SISO) system is used.

The idea of ESO can be explained as follows ((Han, 1995)). For the following system, for instance,

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x_1, x_2, \omega(t), t) + bu \qquad t \geq t_0. \\ y = x_1 \end{cases} \tag{6}$$

where $f(x_1, x_2, \omega(t), t)$ refers to the total disturbance. Let $F(t) = f(x_1, x_2, \omega(t), t)$, and introduce a new variable x_3 as an additional state variable such that $x_3 = F(t)$. Then, the system (6) can be rewritten in the following extended way,

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 + bu \\ \dot{x}_3 = G(t) \\ y = x_1 \end{cases} \quad t \geq t_0. \tag{7}$$

where $G(t)(=\dot{F}(t))$ is unknown to us, and it is the representative of total disturbance.

To estimate the total disturbance, the extended state observer (ESO) ((Han, 1995), (Han, 2009)) for (7) can be built as follows

$$\begin{cases} \dot{x}_1 = x_2 - \beta_0 e \\ \dot{x}_2 = x_3 - \beta_1 e + bu \quad\quad t \geq t_0. \\ \dot{x}_3 = -\beta_2 e \end{cases} \tag{8}$$

Then the system (6) will be forced to change in the following way

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = u_0 \end{cases} \tag{9}$$

which can be obtained by using $u = \frac{u_0 - x_3}{b}$ in (6), and u_0 is the proper combination of the derivative and proportional parts of error variables, which is only for the canonical system (9).

It can be shown that, by properly choosing the parameters in ESO, it can estimate the total disturbance changing to a large extent.

3.3.2 The Implementation of active disturbance rejection control

Based on the methods of TD, NPID, and ESO, which are used for the generation of transient profiles, the nonlinear combination of errors, and the estimation and rejection of total disturbances, respectively, the proposition of ADRC would be a natural thing, and ADRC takes the form as shown in Fig. 1. The corresponding control algorithm and the observer gains can be found in (Han, 1998) or (Han, 2009). As to the tuning of parameters in ADRC, r is the amplification coefficient that corresponds to the limit of acceleration, c is a damping coefficient to be adjusted in the neighborhood of unity, h_1 is the precision coefficient that determines the aggressiveness of the control loop, and it is usually a multiple of the sampling period h by a factor of at least four, and b_0 is a rough approximation of the coefficient b in the plant within a $\pm 50\%$ range.

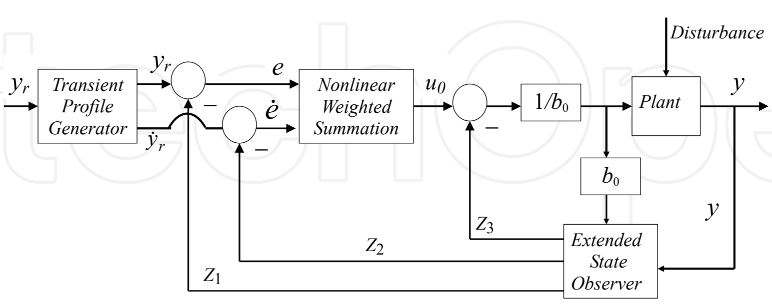

Fig. 1. The control block based on the ADRC

Because of its strong ability to estimate or reject disturbances, ADRC has been widely expanded and it has become a practical and popular control technique, especially in China.

Even though ADRC is presented mainly for a second-order system, it is by no means limited to that. In fact, many complex control systems can be reduced to first or second order systems, and ADRC makes such simplification much easier by lumping many untrackable terms into “total disturbance". Still, the proper problem formulation and simplification is perhaps the most crucial step in practice, and some suggestions are offered as follows ((Han, 1998) or (Han, 2009)).

• Identify the control problem

For a physical process which may contain many variables, one should identify which is the input that can be manipulated and which is the output to be controlled. Maybe this is not very clear, and the choice may not be unique in digital control systems when there are many variables being monitored and many different types of commands can be executed. That is to say, at the beginning, the control problem itself sometimes is not well defined. And it is needed to identify what the control problem is, including its input and output.

• Determine the system structure

According to the relative degree of the system, the structure of the system should be determined. In linear systems, it is easy to obtain the order in terms of its transfer function. For others, such as nonlinear and time varying systems, it might not be straightforward. From the diagram of the plant, the order of the system can be determined simply by counting the number of integrators in it. In the same diagram, however, the relative degree can be found as the minimum number of integrators from input to output through various direct paths.

• Lump the factors which affect the performance

The key in a successful application of ADRC is how well one can reformulate the problem by lumping various known and unknown quantities that affect the system performance into total disturbance. This is a crucial step in transforming a complex control problem into a simple one.

• Proper use of the pseudo control variables

Another effective method for problem simplification is the intelligent use of the pseudo control variable, as shown previously. ADRC shows an obviously quite different way of going about control design. This is really a paradigm shift.

Therefore, the problems of ADRC are that, with the use of ESO, the structure is more complex and it also has more parameters to be tuned. And the implementation needs more skills, especially for some complex industrial processes.

4. The new separation strategy on tuning of PID controllers

In this section, some of the improvements and extensions, which have been done to the active disturbance rejection control (ADRC) in recent years, will be summarized. Firstly, the improvement to ADRC is the proposition of a new separation principle (NSP) such that disturbance rejection and high precision output regulation can be implemented separately. Based on NSP, without using any observer or estimator, disturbances can be rejected, and the output regulation can be carried out effectively even for higher-order systems or multi-input-multi-output interconnected systems. Secondly, in order to meet the needs for the control of uncertain networked systems or complex systems, the NSP is extended and the stripping principle (SP) is proposed. The method based on SP can remove all the interconnected parts, uncertainties and disturbances from the related subsystems, and make the synthesis of complex systems easier and effective. Thirdly, the methods on the stability analysis of the proposed methods will be summed up.

4.1 The new separation principle (NSP) to PID controllers

Based on the necessity analysis above, and from the viewpoint of control system synthesis, if an effective way to reject disturbances and uncertainties can be found, the design for the remaining system will be easier, and the synthesis will have more choices.

4.1.1 The proposition of the new separation principle

It is well known that the variable structure control (VSC) or sliding mode (SM) method has played an important role for disturbance or uncertainty rejection ((Utkin, 1992), (Emelyanov et al., 2000), (Li & Xu, 2010)). But the associated control switching will lead to chattering. PID-type control has a strong ability to reject the uncertainty or disturbance, the tuning of its parameters will need more skills ((Åström & Hagglund, 1995), (Heertjes et al., 2009), (Luo et al., 2009), (Sekara et al., 2009)). At the same time, although active disturbance rejection control (ADRC) can avoid chattering, the need of the extended state observer (ESO) will result in new trouble.

In order to overcome the shortcomings stated above, inspired by the idea of ADRC and the separation principle (SP) ((Blanchini et al., 2009)), it is intended to find a systematic method so that disturbance rejection and high accuracy output regulation can be implemented separately.

• The basic idea of NSP

It is hoped that the PID control input with the form of (1) can be divided into two parts: one is for the rejection of uncertainties and disturbances; the other is for the control of the remaining system which is the one without uncertainties and disturbances. That is to say, it is hope to separate the PID control input into two parts, and each of them has the function of its own. That will reduce the difficulty for the tuning of the parameters.

As a matter of fact, based on the binary control system theory ((Emelyanov et al., 2000)), or by introducing a dynamic mechanism to adjust the gain of the integral feedback, an effective strategy which can powerfully reject disturbances and/or uncertainties will be found. At the same time, by using proper feedback of proportional and derivative (PD) for the remaining parts, the efficient output regulation can be carried out. That is the new separation principle which has been proposed ((Wang, 2010a), (Wang, 2010b), (Wang, 2010e)). The block of the control system based on the new separation principle is shown in Fig.2.

• The implementation of NSP

The dynamic mechanism $\mu(t)$ can be chosen based on the ideas and results of (Emelyanov et al., 2000). One of the particular forms of $\mu(t)$ is as follows, which is described by the following differential equation with a discontinuous right-hand side ((Emelyanov et al., 2000))

$$\dot{\mu}(t) = \begin{cases} -\gamma sgn(\sigma(e)), & \text{as } |\mu(t)| \leq 1, \\ -\omega\mu(t), & \text{as } |\mu(t)| > 1, \quad \mu(t_0) = sgn(\sigma(e(t_0))), \end{cases} \tag{10}$$

where $\sigma(e)$ is a compound function of the regulation error e, γ is a positive parameter, and $\omega(>0)$ is a given positive constant. The purpose of $\mu(t)$ is to adjust the gain of the

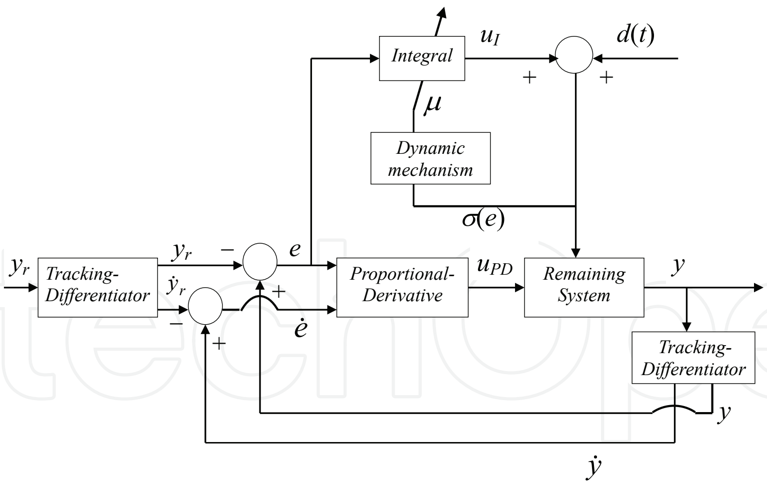

Fig. 2. The control block based on the new separation principle

integral part such that the uncertainties or disturbances can be rejected, in which $\sigma(e)$ can be determined by the parts which should be removed from the system, or equivalently, it should be the part which will be left after the rejection.

It has been proved that, using $\mu(t)$ as (10), the idea of NSP can be realized. The most important of all is that the two procedures (disturbance rejection and output regulation) can be implemented separately. This is the new strategy for PID controller tuning that has been discussed.

Therefore, different from ADRC which uses the following form of control input

$$u = -a_0|e_0|^\alpha sgn(e_0) - a_1|e_1|^\alpha sgn(e_1) - a_2|e_2|^\alpha sgn(e_2) \tag{11}$$

the total control input based on the NSP is the following one

$$u = a_0\mu|e_0|^\alpha - a_1|e_1|^\alpha sgn(e_1) - a_2|e_2|^\alpha sgn(e_2) \tag{12}$$

where e_0 is the integration of the error e_1, a_0 can be determined by the ranges of disturbance and the disturbance's derivative, and the parameters a_1, a_2 can be obtained by assigning, which should maintain the stability of the state (0, 0) of the following remaining error system

$$\begin{cases} \dot{e}_1 = e_2 \\ \dot{e}_2 = -a_1|e_1|^\alpha sgn(e_1) - a_2|e_2|^\alpha sgn(e_2) \end{cases} \tag{13}$$

and in (12), μ can be determined by the following differential equation with a discontinuous righthand side

$$\dot{\mu} = \begin{cases} -\gamma sgn(\dot{e}_2 + a_1|e_1|^\alpha sgn(e_1) + a_2|e_2|^\alpha sgn(e_2)), & \text{as } |\mu| \le 1, \\ -\omega\mu, & \text{as } |\mu| > 1, \quad |\mu(t_0)| \le 1 \end{cases} \tag{14}$$

From the results stated above, it can be seen that the function of integral part is to reject the uncertainties and disturbances, the functions of the proportional and derivative parts are to maintain the stability of the remaining system. Therefore, the tuning of the parameters will be more purposeful. And the most important of all is that the choice of a_0 and a_1, a_2 can be implemented separately.

The benefits of the improvements are as follows: (i) It can transform the synthesis of PID controllers into two separate parts. So it will make the synthesis of systems or the tuning of parameters more convenient; (ii) The functions of the design parameters have the new explanations. It will make the tuning more purposeful; (iii) Without any online estimation of uncertainties or disturbances, or with less design parameters or simple structure, the proposed method can effectively reject uncertain factors; (iv) The method has nothing to do with the structure or the relative degree of the system. That is to say, it can also be extended to the output regulation of higher-order systems, or of multi-input-multi-output (MIMO) interconnected systems; (v) It is because of the improvements that a rigorous theoretic foundation will be laid down for the tuning of PID controllers rather than just solve the tuning problem by rules of thumb or experiments. And this will make it possible that the controllable ranges can be extended to more general uncertain systems. It is because of the robustness to the uncertainties or disturbances that it will be effective for engineering applications.

At the same time, based on the using of tracking-differentiators (TDs) ((Han & Wang, 1994)), a powerful control can be made for tracking targets which are nondifferentiable or even discontinuous, such as sawtooth waves, square waves, or certain random signals etc, even if the output contains measurement noise. And the method also has the ability to deal with random noise, especially of measurement noise. The most important of all is that the two procedures (disturbance rejection and output regulation) stated above can be implemented separately. This is the NSP for PID controller tuning that has been considered.

4.1.2 The comparative analysis

Here some brief comparisons will be given about the differences between the tuning method based on NSP and other typical methods.

First, the method based on the NSP is different from the separation method of PID controller tuning discussed in (Åström & Hagglund, 1995), (Åström & Hagglund, 2004). In (Åström & Hagglund, 2004), the parameters can be determined based on features of the step response, for example, K, T_i, T_d and T_f are determined to deal with disturbances and robustness, and the parameters b and c can then be chosen to give the desired set-point response. And the relevant tuning method is based on rules obtained by a series of experiments. However, for the method from the NSP, the parameters can be chosen based on the empirical estimation of disturbances and the analysis to the structure of the remaining part. There also have some theoretical results to guide the choice. So the tuning will be more purposeful and active. And it is easy to extend the controllable ranges.

Second, the difference between NSP and ADRC ((Han, 2009)) is that, in ADRC the rejection of disturbances is realized by constructing ESO, which may be difficult for some systems with complex structures or that are interrupted seriously by disturbances, and this will need more parameters. But here the rejection of disturbances can be realized by using dynamic feedback, which is just based on estimating the boundaries of the disturbances. The rejection has nothing to do with the relative degree of the controlled systems. So there is a need for small number of design parameters by using NSP.

It seems that the NSP has more parameters to be tuned than the conventional ones, or the structure is more complex than former PID controllers. As a matter of fact, the main parameters in the NSP are a_0 and γ, which can be determined by the theorems given in (Wang, 2010b) or (Wang, 2010e). And the key is that the method of disturbance rejection is independent of the order of the system. The other parameters such as a_1 and a_2 can be chosen by assigning. And the parameters in TDs can be found in (Han, 2009), (Han & Wang, 1994) or (Han & Yuan, 1999). So the tuning is much easier here than that of former ones. It should be emphasized that the choice of those parameters can be accomplished separately.

Of course, the problem of the method based on NSP is that, in u_I (see Fig. 2), the integration about the absolute value of errors is used. It may cause the amplification to the error in disturbances' rejection. This can be avoided by using $|\int_{t_0}^{t} e(\tau)d\tau|$ instead of $\int_{t_0}^{t} |e(\tau)|d\tau$. But such change will have very little influence on the results of output regulation.

As to the computational complexity on obtaining the design parameters, from the results in (Wang, 2010b) or (Wang, 2010e), it is known that the parameters should be estimated only by knowing the boundaries of $d(t)$ and $\dot{d}(t)$. In fact, they can also be obtained by a empirical estimation of the disturbance. It should be noticed that, once certain values of the parameters are satisfactory, the proper changes of them are permissible.

4.2 The Extensions of NSP—the proposition of the stripping principle

In recent years, the control for networked systems or complex systems has attracted increasing attention of scientists or engineers from many fields, especially in some large scale engineering, such as electric grids, communication, transportation, biology systems, and so on, see (Hespanha et al., 2007), (Tipsuwan & Chow, 2003), (Wang, 2010a) or (Wang, 2010b), and the references therein. From a system-theoretical point of view, a networked system can be considered as a large-scale system with special interconnections among its dynamical nodes. For such a class of systems, both the synthesis and the implementation of a centralized controller are often not feasible in practice. Techniques aimed at investigating decentralized or distributed controller architecture have been studied. And many interesting results have been established, for example, decentralized fixed modes, decentralized controller design, diagonal Lyapunov function method, M-matrix method, and the model-based approach, etc. (see (Wang, 2010b) and the references therein). Decentralized control has many advantages for its lower dimensionality, easier implementation, lower cost, etc.

However, due to the structural restrictions in decentralized control, it is very difficult to develop a unified and effective design strategy. As a result, many theoretical and practical problems remain unsolved in this field. And many papers are devoted to stability analysis and decentralized controller design for networked systems with linear forms or the nonlinear terms are restricted to the Lipschitz condition (see (Emelyanov et al., 1992), (Vrancic et al., 2010) and the references therein). At the same time, uncertainties or disturbances are often encountered in many control problems. There is no exception for networked control systems ((Wang, 2010a), (Wang, 2010b)). The existence of uncertainty and/or disturbance will result in more difficulty for the system synthesis. The method of ADRC will face great challenges in such cases.

4.2.1 The basic idea of the stripping principle

Based on the philosophic thinking of 'On Contradiction' ((Mao, 1967)) that one should pay more attention to the principal contradiction or the main factors when dealing with some complicated problems, the stripping principle (SP) has been proposed ((Wang, 2011a)). That is to say, to overcome the difficulties caused by interconnected terms, uncertainties and disturbance, it is hoped to find a systematic method such that the networked control system can get rid of the influence of interconnected parts, uncertainties and disturbances completely. And then the control of networked systems will become a decentralized control for the completely independent subsystems.

Suppose that a dynamical network has N nodes, and different nodes may have different forms of structure or dimensionalities. Each node i $(i = 1, \ldots, N)$ in the network is a continuous-time nonlinear uncertain system described by

$$\begin{cases} \dot{x}_{1i} = x_{2i} \\ \quad \vdots \\ \dot{x}_{r_i i} = f_i(x_i) + \triangle f_i(x_i) + g_i(x^\tau) + d_i(t) + h_i(t)u_i(t) \\ y_i = x_{1i} \end{cases} \tag{15}$$

where $x_i = (x_{1i}, \ldots, x_{r_i i})^\tau$, A^τ means the transpose of A, $f_i(x_i)$ is the main component of node i which is well modelled, $\triangle f_i(x_i)$ is the uncertainty or unmodelled part of the model of node i, and $g_i(x^\tau) = g_i(x_1^\tau, \ldots, x_N^\tau)$ is the interconnected parts which indicate that the subsystem i is affected by other nodes, it may be also unknown to us, $d_i(t)$ is the disturbance, $u_i(t)$ is the control input of the subsystem i, y_i is the output of node i. Suppose that $h_i(t)(\geq h_{0i} > 0)$ is the coefficient of the control input, in which h_{0i} is a constant. Usually, it is supposed that $\triangle f_i, d_i, g_i$ are unknown to us.

In such circumstances, similar to the method based on NSP, for each of the nodes, by introducing integral feedback with a variable gain, a new control method, which can remove the interconnected parts, uncertainties and disturbances, will be obtained. At the same time, the proper nonlinear feedback will be used to realize efficient control for each of the subsystems even if the subsystems are with non-smooth components ((Wang, 2011a)).

4.2.2 The implementation of the stripping principle

As to the implementation of SP, integral feedback with a variable gain will be introduced, or for each subsystem i ($i \in \{1, \ldots, N\}$), let

$$u_i(t) = a_{0i}\mu_i(t) \int_{t_0}^{t} \sum_{i=1}^{N} |x_{1i}(\tau)| d\tau + v_i(t) \tag{16}$$

where $\mu_i(t)$ is a dynamic mechanism, $v_i(t)$ is the new control input for the remaining parts of the subsystem i. It has been proved that, through the proper choice of $\mu_i(t)$ similar to (10), all the non-principal factors, such as the interconnected parts, uncertainties and disturbances, can be removed from the subsystem i by using the control input with the form of (16).

If the interconnected parts, uncertainties and disturbances are taken away from the subsystem i, the new control input $v_i(t)$ can be chosen as the one which depends on the control performance of the subsystem i. The simple one of $v_i(t)$ can be obtained by using the principle of poles' placement when the subsystems are linear systems, i.e., $v_i(t)$ can be taken as the following form:

$$v_i(t) = -\sum_{j=1}^{r_i} a_{ji} x_{ji}(t) \tag{17}$$

where $a_{ji}(> 0)$ can be chosen according to the requirement of poles or the performance of the subsystem i.

For the subsystems which are with nonlinear forms, and in order to improve the efficiency of the output regulation, based on the idea of nonlinear PID controllers ((Han, 1994)), the control variable $v_i(t)$ can be chosen as follows ((Wang, 2011a)):

$$v_i(t) = -\sum_{j=1}^{r_i} a_{ji} |x_{ji}(t)|^{\alpha} sgn(x_{ji}(t)) \tag{18}$$

where $0 < \alpha \leq 1$ and $a_{ji}, (j = 1, \cdots, r_i)$ are the design parameters as that of (17).

As far as the existence of γ_i and a_{0i} are concerned, it is needed only to assume that, for certain constants $\bar{k}_i$ and $\bar{\bar{k}}_i$, the following inequalities

$$|\max_{0<\tau\leq t}\{d_i, \triangle f_i, g_i\}| \leq \int_0^t \sum_1^N |x_{1i}(\tau)| d\tau + \bar{k}_i \tag{19}$$

and

$$|\max_{0<\tau\leq t}\{\dot{d}_i, \frac{d}{d\tau}[\triangle f]_i, \dot{g}_i\}| \leq \int_0^t \sum_1^N |x_{1i}(\tau)| d\tau + \bar{\bar{k}}_i \tag{20}$$

hold in the meaning of supremum.

In fact, from the basic conclusions of ordinary differential equations (Emelyanov et al., 2000) and (Filippov, 1988), it is known that, for a positive constant k, if a function $v(t)$ satisfies the following inequality

$$|v(t)| \leq k + \int_0^t \kappa(s)|v(s)| ds \tag{21}$$

then the usual Gronwall inequality can be obtained as follows:

$$|v(t)| \leq k\, exp\left(\int_0^t \kappa(s) ds\right) \tag{22}$$

Therefore, if $|x_1(t)| \leq k_0 + \int_0^t |x_1(\tau)| d\tau$, then $x_1(t)$ will be dominated by a exponential function. On the contrary, it can be proved that if the variation of $x_1(t)$ does not exceed certain exponential functions, the inequality of (21) holds. Then, as long as (19) and (20) hold, the γ_i and a_{0i} can be found so that the disturbance can be rejected. And from (19) and (20), it is known that there are a large number of functions satisfying the restrictions. Of course, step-like functions belong to the set which can be rejected in this way. It also indicates that the Lipshitz condition, which will be required for the analysis of uncertain systems by using some of the other methods ((Emelyanov et al., 1992), (Vrancic et al., 2010)), will not be necessary.

In (20), the derivatives of the uncertainties will be needed. It can be replaced by the existence of the generalized derivatives when those uncertainties are nondifferentiable. And, in (12) and (16), the integration of absolute value of states or errors will be used, then the gains of those expressions will be infinite as $t \to \infty$, so it is capable of rejecting the disturbance such as random noise, even though the derivative of random noise does not exist.

From the above results it is known that, in contrast to other methods, the improvements and extensions on disturbance rejection have nothing to do with the relative degree or the interconnected terms of systems. Therefore the method has less requirements for the systems' structure. That will greatly reduce the complexity for obtaining the design parameters.

4.2.3 The benefits of the stripping principle

The benefits of the method based on the stripping principle are as follows: (i) It can transform the control of networked systems into decentralized control. So it can make the synthesis more convenient; (ii) Without any online estimation of uncertainties, disturbances, or interconnected parts, or with less design parameters or simple structures, the proposed method can effectively reject the troublesome factors; (iii) The functions of the design parameters also have the new explanations. It will make the synthesis of the control system more purposeful; (iv) It is the method that a rigorous theoretic foundation will be laid down for the control method rather than just solve the problem by rules of thumb or experiments. And this will make it possible that the controllable ranges can be extended to more general uncertain networked systems. It is the benefits of the control system that a controller with a simple structure and less parameters to be tuned will be obtained. And it is because of the robustness to the uncertainties or disturbances, then it is easy for engineering implementation.

Theoretical analysis is provided to guarantee the possibility of the method and the stability of the relevant control systems.

4.3 The stability analysis of the relevant control systems

Similar to the synthesis method which uses two separated parts, the stability analysis of the control systems can also be divided into two parts. The first one is to determine the condition to keep the states on a 'variable sliding mode'. The second one is to find the stability condition for the remaining parts (Wang, 2010e).

Firstly, to the stability condition for the disturbance rejection, the following Lyapunov function can be used:

$$L_i(\sigma_i(x_i)) = \frac{1}{2}\sigma_i^2(x_i), \ \ i = 1, \dots, N \tag{23}$$

where $\sigma_i(x_i)$ is the part of the non-principal factors of node i which will be stripped, or equivalently, the remaining part after the stripping of the non-principal factors. Based on the condition discussed in (Emelyanov et al., 2000) and (Filippov, 1988), it is known that, under the restrictions of (19) and (20), $\sigma_i(x_i)$ will converge to zero asymptotically.

Secondly, the stability condition for the remaining parts is easy to be obtained. In fact, the parameters such as a_1, a_2 in (13) or $a_1, \cdots, a_n$ in (17) can be chosen by using placement of poles. Especially, for linear error systems, the parameters can be chosen based on the Hurwitz rules ((Emelyanov et al., 2000)), or the optimal control method.

If the remaining system is a second-order linear system, the nonlinear feedback as (13) can be chosen. In such a case, the Lyapunov function can be chosen as follows:

$$L_2(x_1, x_2) = \frac{a_1}{\alpha + 1}|x_1|^{\alpha+1} + \frac{1}{2}x_2^2 \tag{24}$$

From the Krasovskii theorem, it is known that the remaining system is stable ((Han & Wang, 1994)). For other kinds of remaining systems, the Lyapunov function can be chosen similarly.

So with the Lyapunov functions of (23) and (24), the stability of the whole system can be proved. It means that the stability of the whole control system can be easily guaranteed.

5. Some applications

In this section, some of the applications are provided to demonstrate the effectiveness of the new methods discussed in section 3 and 4. The applications include the control for tracking unusual motion patterns, the safety and comfort control of vehicles, the active control for noise suppressing, and the synchronization control of networked systems, etc.

5.1 The control for tracking unusual control patterns

The control on output tracking for some unusual control patterns was considered in (Wang, 2010d) by using ADRC. Here, just some simulation results are selected. The simulation can be carried out by using Matlab. In all simulations, let $\omega = 0.5$ in (14). Other parameters can be chosen based on certain given situations.

Consider the following second-order nonlinear system

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_1^2 + 1.5x_2^2 + 4.9sin(t) + u \\ y = x_1 \end{cases} \tag{25}$$

where $4.9sin(t)$ can be regarded as a term of disturbance. It is hoped that the output $y = x_1$ can follow the reference signal y_r, in which the reference inputs y_r are chosen in the form of square and sawtooth waves, respectively. Owing to the nondifferentiable of the reference signals, a TD can be used to smooth y_r. Here, for the purpose of precision, the discrete form of TDs ((Han & Yuan, 1999)) is used. The parameters in TD are chosen as $r = 30, h = 0.01, T = 0.01$. The parameters in (12) are given by $a_0 = 20, a_1 = 90, a_2 = 90$. And the parameters of ω, γ are 0.5 and 10 respectively. The results on output tracking of the two cases are shown in Fig. 3 and Fig. 4 respectively.

The results indicate that, with the using of TDs, the method can deal with the signals which are nondifferentiable, generate the proper transient profile, and implement the output regulation effectively.

5.2 The control of higher-order systems

The method based on NSP will demonstrate great potentialities to the control of higher-order systems, for example, the control for the safety and comfort of vehicles ((Wang, 2010a)).

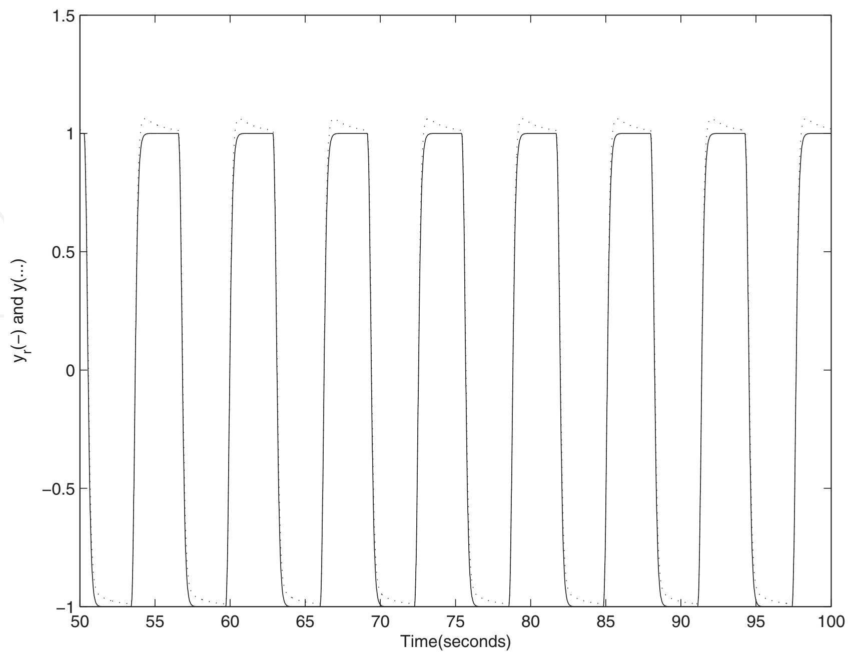

Fig. 3. The output result of tracking the square wave

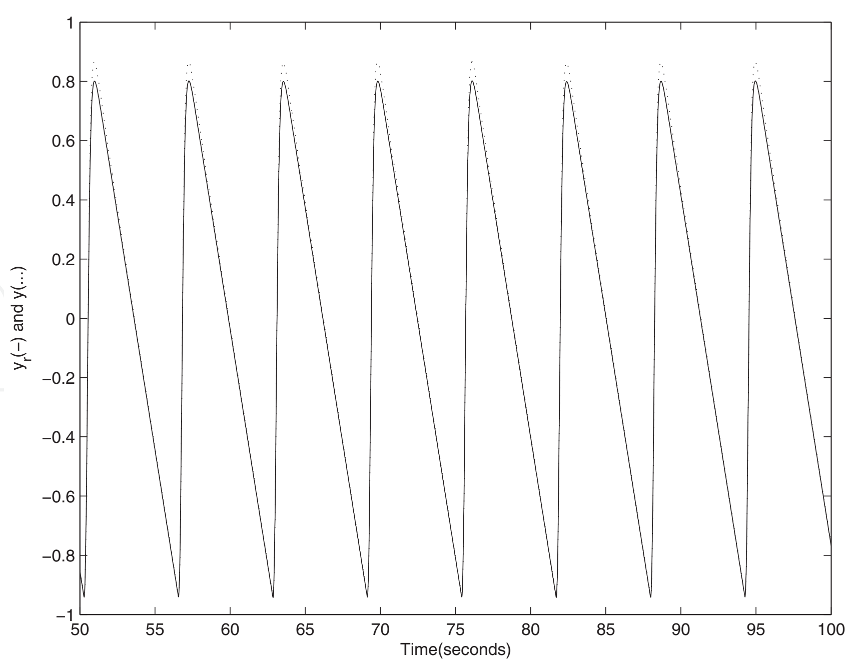

Fig. 4. The output result of tracking the sawtooth wave

Usually, the model of vehicles is a three-order differential equation, so it is easy to be controlled by using the method based on NSP. As an example, the three-order system is considered as follows:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 \\ \dot{x}_3 = 0.3x_1 - 0.2x_2x_3 - x_3 + 0.4x_2^2 + 3sin(t) + 2 + d_1(t) + u \\ y = x_1 + \delta n(t) \end{cases} \tag{26}$$

where $d_1(t)$ refers to the disturbance, which is the possible influence of the road, it can be simulated by the stochastic process obtained from signal generator (SG) of Matlab with the type of random and the parameter of amplitude is 5. The measurement noise can be obtained by random number (RN) with the coefficient of δ. The output $y = x_1$, and its derivatives $\dot{y} = \dot{x}_1$, $\ddot{y} = \ddot{x}_1$ and $\dddot{y} = \dddot{x}_1$ refer to the location, velocity, acceleration and jerk of the vehicle, respectively. The satisfactory control results for all the state variables can be obtained ((Wang, 2010a)).

Another example is the control of a fourth-order system. Consider a flexible joint robotic system which is a single-link manipulator with a revolute joint actuated by a DC motor, and the elasticity of the joint is modelled as a linear torsional spring with stiffness K (see Fig.1 in (Talole et al., 2009) for details). By introducing certain coordinates to the system, its mathematical model is the one as follows, which can be found in (Talole et al., 2009)

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 \\ \dot{x}_3 = x_4 \\ \dot{x}_4 = a(x) + d_2(t) + bu \\ y = x_1 + \delta n(t) \end{cases} \tag{27}$$

where $x = (x_1\ x_2\ x_3\ x_4)^\tau$, $a(x) = \frac{MgL}{I} sin(x_1) \left(x_2^2 - \frac{K}{J} \right) - \left(\frac{MgL}{I} cos(x_1) + \frac{K}{J} + \frac{K}{I} \right) x_3$ and $b = \frac{K}{IJ}$. The parameters of the system can also be found in (Talole et al., 2009). Different from the method discussed in (Talole et al., 2009) which uses linearization and ESO, the cascade of TDs are used to obtain the estimation of the states, and the disturbance $d_2(t)$, which is the type of random variable obtained from SG of Matlab with the parameter of amplitude 2, is also introduced. The satisfactory results, especially with good performance can still be obtained ((Wang, 2011c)).

These results indicate that, even if the system contains disturbance, the method based on NSP is not only with a simple control structure but also has strong ability to the control of higher-order systems.

5.3 The noise suppression by using active control based on the NSP

To indicate the ability of the control method for disturbance rejection, the results on noise suppression based on the NSP is demonstrated, the example is considered as follows.

For the following form of noise

$$n_1(t) = rand * sawtooth * square + rand + sin(4t) + 30 \tag{28}$$

where *rand* is the the random signal, and *sawtooth*, and *square* are sawtooth and square waves respectively, and the amplitude and frequency of *sawtooth, and square* are 2, 10 and 1, 5 respectively. It is hoped to suppress $n_1(t)$ to zero. The control method based on the NSP is used. The noise suppression result can be shown in Fig.5. The more details and results can be found in (Wang, 2010c).

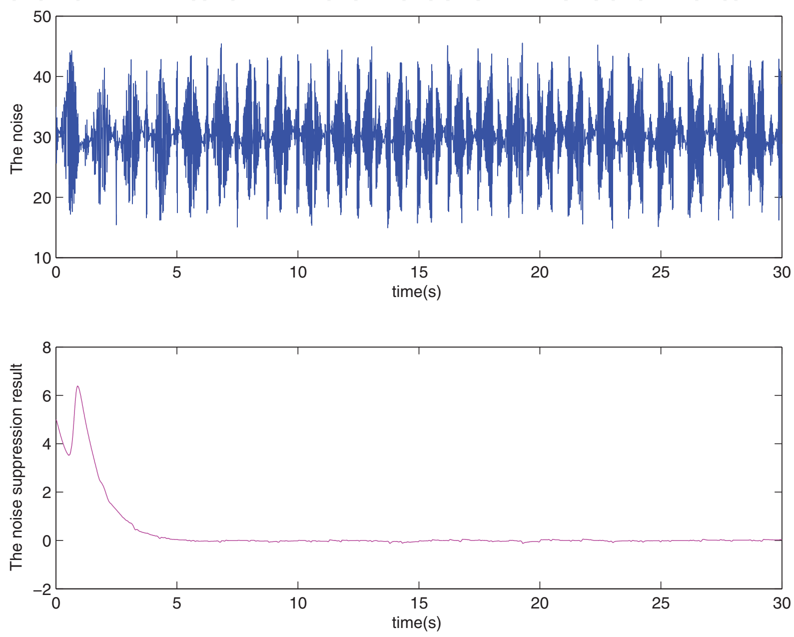

Fig. 5. The noise suppression result based on the new separation principle

The result indicates that the method of NSP has strong ability for rejecting noise, even if the noise is a colored one.

5.4 The control of interconnected dynamical systems

The control results on general unstable interconnected systems can be found in (Talole et al., 2009) and (Foo & Rahman, 2010). Here, an example on the application of the control method based on NSP for some practical MIMO systems is provided.

For an interior permanent-magnet synchronous motor (IPMSM) which has been considered extensively in recent years (see (Foo & Rahman, 2010) and the references therein), the model can be described by the following equation

$$\frac{dx}{dt} = f(x) + g(x)u \tag{29}$$

where $x = (i_d \; i_q \; \omega_r)^\tau$, $u = (v_d \; v_q)^\tau$, $g(x) = \begin{pmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \\ 0 & 0 \end{pmatrix}$, and

$$f(x) = \begin{pmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \end{pmatrix} = \begin{pmatrix} -\frac{R}{L_d} i_d + P\frac{L_q}{L_d} i_q \omega_r \\ -\frac{R}{L_q} i_q - P\frac{L_d}{L_q} i_d \omega_r - P\frac{\lambda_f}{L_q}\omega_r \\ \frac{3}{2}P\frac{(L_d-L_q)}{J} i_d i_q + \frac{3}{2}P\frac{\lambda_f}{J} i_q - \frac{B}{J} - \frac{T_L}{J} \end{pmatrix} \tag{30}$$

and the meanings and their values of the parameters in (29) and (30) can be found in (Foo & Rahman, 2010).

It is evident that it is a MIMO interconnected system. It is hoped that the outputs i_d and ω_r can track the reference values $i_d^* = \frac{L_d-L_q}{\lambda_f} i_q^2$ and ω_r^* respectively. By introducing the error variables $e_1 = i_d - i_d^*, e_2 = \omega_r - \omega_r^*$, the following error system can be obtained

$$\begin{pmatrix} \dot{e}_1 \\ \ddot{e}_2 \end{pmatrix} = \begin{pmatrix} \tilde{f}_1 \\ \tilde{f}_2 \end{pmatrix} + \tilde{G}u \tag{31}$$

where

$$\tilde{f}_1 = f_1(x) - 2i_q \frac{L_d - L_q}{\lambda_f} f_2(x),$$
$$\tilde{f}_2 = \frac{3}{2}P\left(\frac{L_d - L_q}{J}\right) f_1(x) i_q + \frac{3}{2}P\left(\frac{L_d - L_q}{J}\right) f_2(x) i_d + \frac{3}{2}P\frac{\lambda_f}{J} f_2(x) - \frac{B}{J} f_3(x),$$

and

$$\tilde{G} = \begin{pmatrix} \frac{1}{L_d} & -\frac{2(L_d-L_q)}{L_q\lambda_f} i_q \\ \frac{3}{2}\frac{P}{J}\frac{(L_d-L_q)}{L_d} i_q & \frac{3}{2}\frac{P}{J}\frac{[\lambda_f+(L_d-L_q)i_d]}{L_q} \end{pmatrix}$$

in which $f_1(x), f_2(x)$ and $f_3(x)$ are the ones given in (30).

Let $u = \tilde{G}^{-1}(v_1, v_2)^\tau$, this can realize the decoupling to the error system (31). Then v_1, v_2 can be chosen respectively. From the structure of this error system, for the control of i_d, PI control is used, and for the control of ω_r, PID-type control is used. Compared with the method used in (Foo & Rahman, 2010), without the help of other control such as artificial intelligent (AI), satisfactory results can still be obtained. The structure of the control system here is also a simple one (Wang, 2011c).

It should be emphasized that, if the form of the model or the design parameters are changed in certain ranges, the results on the output regulation may have almost no change at all.

5.5 The synchronization control of complex dynamical networks

In (Wang, 2011b), the output synchronization control is considered for following networked system with three second-order coupled nonlinear subsystems

$$\begin{cases} \dot{x}_{11} = x_{21} \\ \dot{x}_{21} = \sum_{j=1}^{3} f_{j1}(x_1, x_2, x_3) + d_1 + u_1 \\ \dot{x}_{12} = x_{22} \\ \dot{x}_{22} = \sum_{j=1}^{3} f_{j2}(x_1, x_2, x_3) + d_2 + u_2 \\ \dot{x}_{13} = x_{23} \\ \dot{x}_{23} = \sum_{j=1}^{3} f_{j3}(x_1, x_2, x_3) + d_3 + u_3 \\ y = (x_{11}, x_{12}, x_{13}) \end{cases} \tag{32}$$

in which $x_i = (x_{1i}, x_{2i})^\tau, i = 1, 2, 3$ are the states of the subsystems, $f_{11} = sin(x_{11}) + x_{21}^2$, $f_{22} = x_{12}^2 + x_{22}^2$, $f_{33} = -x_{13}^2 + x_{23}^2$, $f_{21} = f_{23} = -sin(x_{12}) - x_{22}$, $f_{31} = f_{32} = sin(x_{13}) + x_{23}$, $f_{12} = f_{13} = sin(x_{11}) + x_{21}$ are the interconnected terms. $d_1(t) = 5sin(t) + 3, d_2(t) = 3sin(t) + 5$, $d_3(t) = 3cos(t) + 6$ can be regarded as terms of disturbances. Obviously, the subsystems are unstable.

It is hoped that the outputs x_{11}, x_{12}, x_{13} can synchronize with the filtered random signal. Owing to the need of obtaining the higher-order derivatives, the discrete form of TDs ((Han & Yuan, 1999)) is used, and the parameters in the TD are chosen as $r = 30, h = 0.01, T = 0.01$. The parameters in (12) are given by $a_{0i} = 30, a_{1i} = 80, a_{2i} = 80$ and $\alpha = 0.6$. And the parameters of ω, γ_i in (14) are 0.5 and 10 respectively. The results on the synchronization control of the three subsystems are shown in Fig. 6. The more results can be found in (Wang, 2011b).

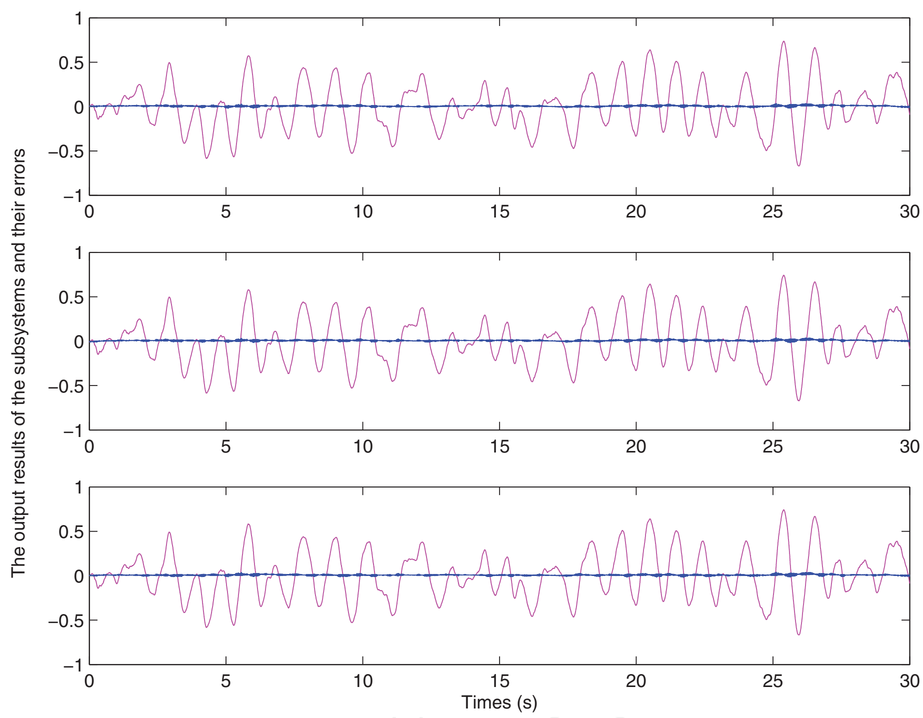

Fig. 6. The output synchronization of networked system

From all these simulation results, it is known that the parameters of γ and ω in the dynamic mechanism $\mu(t)$ can be chosen almost the same. That is to say, they are about 10, and 0.5, respectively.

The results of these applications show that the control methods based on the new strategy can not only have a fast response but also with a strange stability, even if the controlled system contains uncertainty or disturbance, or even has a complex structure. In addition, the methods can also deal with noise effectively.

And, for the usage of these methods, more attention should be paid mainly for choosing the coefficients of the control inputs, and the choice of the coefficients may be carried out separately or purposefully. So it will make the tuning of PID controllers easier.

6. Conclusions

In this chapter, a summary is provided on the improvements and extensions related to the tuning of PID controllers, which have been done from another point of view in recent decades. The development of ADRC is an important step to the improvement of PID control. The new separation principle (NSP) is an another essential improvement of PID control. That is to say, in order to overcome the shortcomings mentioned above, inspired by the idea of the binary control system theory ((Emelyanov et al., 2000)) and the separation method of PID control((Åström & Hagglund, 2004)), a systematic method was proposed so that disturbance rejection and high accuracy output regulation can be implemented separately ((Wang, 2010a)). The extension of NSP is the proposition of the stripping principle (SP) which can provide an effective systematic method for the control of networked systems or complex systems. The method based on SP can remove all the non-principal factors, and it transforms the synthesis of complex systems into decentralized control, so it makes the implementation easier. The efficiency of the related methods is shown by some applications. These methods also have a great potential value for the control of practical complex systems.

As to the problem on how to make the idea more suitable for practical applications, it will be considered in the future.

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First placed on the market in 1939, the design of PID controllers remains a challenging area that requires new approaches to solving PID tuning problems while capturing the effects of noise and process variations. The augmented complexity of modern applications concerning areas like automotive applications, microsystems technology, pneumatic mechanisms, dc motors, industry processes, require controllers that incorporate into their design important characteristics of the systems. These characteristics include but are not limited to: model uncertainties, system's nonlinearities, time delays, disturbance rejection requirements and performance criteria. The scope of this book is to propose different PID controllers designs for numerous modern technology applications in order to cover the needs of an audience including researchers, scholars and professionals who are interested in advances in PID controllers and related topics.

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