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滑模控制和自抗扰控制的研究进展

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摘要: 本文概括了滑模控制和自抗扰控制的研究进展, 进一步给出了复合控制的思想. 滑模控制和自抗扰控制都有它们各自的优点，但是也都有它们各自的局限, 例如: 滑模控制中的抖振问题和自抗扰控制中的估计能力受限问题. 复合控制结合了滑模控制和自抗扰控制的优点, 并能提高闭环系统的性能.

关键词: 复合控制; 滑模控制; 自抗扰控制; 稳定性
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Recent developments in sliding mode control and active disturbance rejection control

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Abstract: Rencent developments on sliding mode control (SMC) and active disturbance rejection control (ADRC) are summarized. The concept of compound control is also introduced. SMC and ADRC have their own advantages and limitations, i.e., chattering of SMC and the observability of extended state observer (ESO). Compound control combines their advantages and improves the performance of the closed-loop systems.

Key words: compound control; sliding mode control; active disturbance rejection control; stability

1 Brief introduction of sliding mode control

It is well known that the sliding mode control (SMC) has attractive features to keep the systems insensitive to uncertainties on the sliding surface; its applications have been extensively studied in [1–4]. SMC is a control method whose structure is intentionally changed with a discontinuous control which drives the phase trajectory to a stable hyperplane or manifold. The high-speed switching forces the state to slide along the hyperplane until it converges, which is shown in Fig.1.

$$u(t) = \begin{cases} u^+(x),\ s(x) > 0, \\ u^-(x),\ s(x) < 0. \end{cases} \quad (1)$$

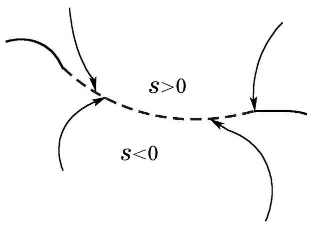

Fig. 1 Attracted by sliding surface

It requires:

1) The existence of the surface.

2) Satisfying the reaching condition. Design the controller to ensure that the trajectory of the closed-loop system can be driven onto the sliding surface in finite time.

3) The stable movement on the surface.

In the discrete-time system, the control input is calculated once in every sampling interval and is held constant in the sampling period. This means that the structure of an discrete sliding mode control (DSMC) may be changed only at discrete instants, which is in contrast to its continuous counterpart whose structure switching may be made at any instant, once the state trajectories cross the switching surface. Thus, the finite sampling rate results in that the system state in DSMC may approach the switching surface but is generally unable to stay on it. As a result, it would move back and forth between surfaces, which yields a sliding-like mode, termed as quasi-sliding mode (QSM), which is shown in Fig.2.

It is well known that SMC is a robust method to control nonlinear and uncertain systems, which has attractive features to keep the systems insensitive to the uncertainties on the sliding surface. The conventional

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SMC design approach consists of two steps. First, a sliding manifold is designed such that the system trajectory on the manifold acquires certain desired properties. Then, a discontinuous control is designed such that the system trajectories will reach the manifold in finite time. SMC as a general design tool for control systems has been well established, the primary advantages of SMC are: I) fast response and good transient performance; II) robustness against a large class of perturbations or model uncertainties; and III) the capability of stabilizing some complex nonlinear systems which are difficult to be stabilized by continuous state feedback laws.

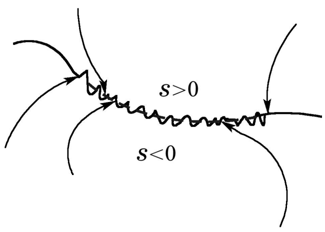

Fig. 2 Quasi-sliding mode

2 Recent development of SMC

2.1 Discrete-time SMC

A discrete version of SMC is important when it is realized/implemented digitally with a relatively slow sampling period. Furthermore, DSMC cannot be obtained from their continuous counterpart by means of simple equivalence. In [5], the problem of discrete variable structure control (VSC) was first considered. The concept of the QSM was suggested in [6], and phenomena of switching, reaching, and QSM were investigated in [4]. In [7], a robust DSMC for uncertain linear systems with unknown time-varying state delay is analyzed, in which uncertainties consist of mismatched uncertain parameters and unknown bounded nonlinear function.

2.2 Output feedback SMC

It is well known that the SMC has attractive features to keep the systems insensitive to the uncertainties on the sliding surface, its applications have been extensively studied in [8–9]. In [10], a dynamic output feedback SMC algorithm is proposed for linear mulit-input and multi-output (MIMO) systems with mismatched norm-bounded uncertainties along with disturbances and matched nonlinear perturbations. Ref. [11] investigates the use of a sliding mode controller and an equivalent output injection sliding mode observer to control a nonlinear plant in the presence of an unknown disturbance. In [12], a sliding mode controller equipped with a sliding mode observer is synthesized and applied to a novel three-axis fourwire optical pickup for sensorless tilt compensation.

2.3 Adaptive SMC

Due to the widespread use of digital controllers, many researches have been done on DSMC based on state-space models [13], in which the bound of the uncertainties and disturbances are assumed to be known. In [14], the resilient adaptive control of discrete-time linear systems has been developed. In [15], a design scheme of robust adaptive controller is obtained by combining the back-stepping technique with parameter projection. In [16], a discrete adaptive SMC is investigated for delta operator systems.

2.4 Intelligent SMC

In [17], soft computation is developed in intelligent systems, providing alternative means for adaptive learning and control to overcome the key SMC technical problems. In [18], an adaptive multi-model SMC using soft computation is designed for robotic manipulators. In [19], a decentralised intelligent double integral sliding mode control (IDISMC) system is presented, in which five IDISMCs are included to regulate and stabilize a fully suspended five-degrees-of-freedom (DOF) active magnetic bearing (AMB) system. In [20], a fuzzy-neural sliding mode (FNSM) control system is designed to control power electronic converters.

2.5 Finite-time control

Discontinuous terminal sliding mode (TSM) control has been widely applied to robotic manipulators for finite-time stability. However, the negative fractional powers existing in the TSM control may cause the singularity problem around the equilibrium[21]. Recently, a discontinuous nonsingular TSM control scheme has been developed to avoid this problem[22]. In [23], two robust controllers based on quaternion feedback are proposed to achieve the attitude tracking of a rigid spacecraft in finite time. Ref.[24] proved that a general uncertain single-input-single-output (SISO) regulation problem is solvable only by means of discontinuous control laws, giving rise to the so-called high-order sliding modes. In [25], the attitude stabilization for rigid spacecraft is considered and the TSM method is employed such that the states can in finite time converge into a small region of the origin in the presence of external disturbance. In [26], smooth second-order SMC with finite-time convergence is developed to enforce hit-to-kill guidance strategy in the presence of target maneuvers and dynamic uncertainty of airframe-actuator.

3 Brief introduction of active disturbance rejection control (ADRC)

ADRC was firstly proposed by Han in [27–29], explained carefully by Han in [30], analyzed in depth by Gao in [31] and Huang in [32]. The stability of extended state observer (ESO) has been obtained by Huang in [33]. The boundary stabilization of a one-dimensional anti-stable wave equation subject to boundary disturbance based on two strategies, namely, SMC and ADRC respectively has been achieved by Guo in [34]. Furthermore, Professor Guo gives the convergence rigorous proofs of tracking differentiator (TD), nonlinear high-gain TD and ESO under some additional conditions in [35–37], respectively. ADRC is a new non-linear algorithm used in different fields in recent years, it has been proposed and developped for almost two decades, and its applications can be found in lots of literature in recent years. It is a control method that does not depend on the accurate mathematical model of the unknown object. By real-time estimation and compensations of the internal and external disturbances of system, combining with nonlinear control strategy, it can get better static and dynamic performances, strong robustness and adaptability. Since ADRC does not depend on the accurate model of the system, it is very robust against parameter variations, disturbances and noises, not only in some operation areas but also in the whole working area.

3.1 ADRC strategy

Classical proportional-integral-derivative (PID) is a particular primitive and simplified implementation of the basic principle in error-based feedback control, which focuses on eliminating the control error by using the current, past and future states of the feedback error.

PID control law is

$$u = k_0 e + k_1 \int_0^t e(\tau)\mathrm{d}\tau + k_2 \dot{e},$$

where $\int_0^t e(\tau)$, e and $\dot{e}$ are integral of error, error and error change rate, and k_0, k_1, k_2 are respectively proportional gain, integral gain and derivative gain coefficient. There is a question, that if the load changes in a very large range, we can not change the parameters online to meet the system requirements. However, the ADRC method which doesn't depend on system model can estimate and compensate the effects of all the internal and external disturbances in real-time. ADRC not only has the same advantages of fast response and strong robustness as traditional PID control theory, but also gives a new control theory and control method which is widely applied for its excellent system performances.

The ADRC consists of three parts, a nonlinear TD which is used to obtain the ideal transient process of the system, an ESO which estimates all the disturbances by the system output, and then the ADRC compensates the disturbance according to estimated values, a nonlinear state error feedback (NLSEF) which is used to get the control input of the system. The structure of ADRC controller is shown in Fig.3. Consider system

$$\begin{cases} x_1 = y, \\ \dot{x}_1 = x_2, \\ \dot{x}_2 = f(x_1, x_2, \omega(t), t) + bu, \end{cases}$$

where y is the output variable, u is the control variable, b is the magnification factor and $\omega(t)$ is the external disturbance. $f(x_1, x_2, \omega(t), t)$ is the total external and internal disturbance function. The ADRC approach compensates for the unknown dynamics and external disturbances in the domain time.

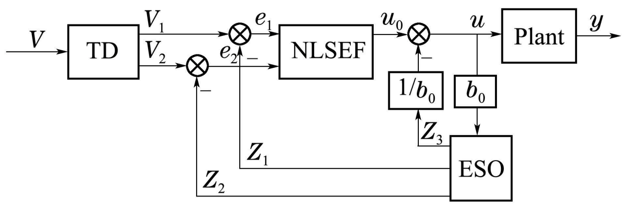

Fig. 3 The structure of ADRC algorithm

In this approach, the error from unmodelled dynamics and disturbances is estimated using an ESO and is compensated during each sampling period. Since uncertainties and disturbances are estimated and compensated via the ESO, there is no need for integral control. This method was developed by Professor Jingqing Han. The proposed ADRC control system consists of the TD, the ESO and a nonlinear PD controller. It is designed under the assumption of high degree of model uncertainties. The controller is designed to be inherently robust against plant variations. Once it is set up for the problem within a predetermined range of variation in system variables, no tuning is needed for start-up, or to compensate for changes in the system dynamics and disturbance. This method, because of its robustness and disturbance rejection capabilities, is particularly suitable for system control.

3.2 TD

It is common in PID control that a differentiation of a signal v is obtained approximately as

$$y = \frac{s}{\tau s + 1} v, \tag{2}$$

which can be rewritten as

$$y = \frac{1}{\tau}(1 - \frac{1}{\tau s + 1}) v, \tag{3}$$

or in the time domain as

$$y(t) = \frac{1}{\tau}(v(t) - v(t - \tau)) \approx \dot{v}(t), \tag{4}$$

if $v(t)$ contains noise $n(t)$,

$$y(t) = \frac{1}{\tau}(v(t) + n(t) - v(t - \tau)) \approx \dot{v}(t) + \frac{1}{\tau} n(t),$$

then $\dot{v}(t)$ contains $n(t)/\tau$ in its first term in Eq.(3). We therefore conclude that Eq.(2) is not a good way in approximating $\dot{v}(t)$. Instead, we propose the following approximation:

$$\dot{v}(t) = \frac{v(t - \tau_1) - v(t - \tau_2)}{\tau_2 - \tau_1},$$

which can be implemented approximately using the second order transfer function

$$w_1(s) = \frac{1}{\tau_2\tau_1}(\frac{1}{\tau_1 s+1} - \frac{1}{\tau_2 s+1}),\ \tau_2 > \tau_1 > 0.$$

Here, as verified in simulations, this resolves the aforementioned problem of noise amplification. The performance of some control systems is restricted by the differential signals selected from the noncontinuous noisy measured signals. The differential signal is usually obtained by the backward difference of the given signal, but it will contain a certain amount of stochastic noise. However, TD has the ability to resolve the problem of differential signal extraction via integration. Therefore, it can avoid unnecessary noise and make the system more effective and robust in some situations.

One feasible second-order TD can be designed as

$$\begin{cases} \dot{v}_1 = v_2, \\ \dot{v}_2 = \mathrm{fhan}(v_1 - v(t), v_2, r, h_0), \end{cases}$$

where $v(t)$ denotes the control objective, r is the speed factor which decides tracking speed. The greater value of r is, the faster transition process will be. Here h_0 is the filtering factor which makes an effort of filtering. As we know, decreasing the integration step will make a great effect on limiting the noise. When the integration step is fixed, increasing the filtering factor will make the filtering effect better. The function is defined as follows:

$$\mathrm{fhan}(v_1 - v(t), v_2, r, h_0):$$
$$\begin{cases} d = rh_0^2, \\ a_0 = h_0 v_2, \\ y = (v_1 - v(t)) + a_0, \\ a_1 = \sqrt{d(d+8|y|)}, \\ a_2 = a_0 + \mathrm{sgn}\, y \cdot (a_1 - d)/2, \\ s_{\mathrm{y}} = (\mathrm{sgn}(y+d) - \mathrm{sgn}(y-d))/2, \\ a = (a_0 + y - a_2)s_{\mathrm{y}} + a_2, \\ s_a = (\mathrm{sgn}(a+d) - \mathrm{sgn}(a-d))/2, \\ \mathrm{fhan} = -r(\frac{a}{d} - \mathrm{sgn}\, a)s_a - r\mathrm{sgn}\, a. \end{cases}$$

The TD is such a nonlinear component which provides transition process for expected input v and differential trajectory of v_1 and its differential v_2. TD has the ability to track the given input reference signal with fast response and no overshoot.

3.3 ESO

$f(x_1, x_2, \omega(t), t)$ generally includes three parts: modeling dynamics, uncertain dynamics (or uncertain accelerations) and disturbance; it is difficult to get the exact model of $f(x_1, x_2, \omega(t), t)$ or its approximation. ESO is used to estimate $f(x_1, x_2, \omega(t), t)$ in real-time and to make adjustments at each sampling point in a digital controller. Here $f(x_1, x_2, \omega(t), t)$ is considered an extended state for the system, x_3 is the uncertaintie $f(x_1, x_2, \omega(t), t)$, and its differential $a(t)$.

We can rewrite this system as follows:

$$\begin{cases} x_1 = y, \\ \dot{x}_1 = x_2, \\ \dot{x}_2 = x_3 + bu, \\ \dot{x}_3 = a(t), \end{cases}$$

then, we can use the following nonlinear observer to estimate x and $f(x_1, x_2, \omega(t), t)$:

$$\begin{cases} e = z_1 - y, \\ \dot{z}_1 = z_2 - \beta_1 e, \\ \dot{z}_2 = z_3 - \beta_2 \mathrm{fal}(e, \alpha_1, \delta) + b_0 u, \\ \dot{z}_3 = -\beta_3 \mathrm{fal}(e, \alpha_2, \delta), \end{cases}$$

where z_1, z_2 and z_3 are the observer outputs and β_1, β_2 and β_3 are observer gains, e is the error, z_1 is used to estimate the system output, z_2 is used to estimate the differential of the system output, z_3 is the extended state variable to estimate comprehensive disturbances. Parameters β_1, β_2 and β_3 must be tuned appropriately to achieve the good performance.

3.4 Nonlinear combination

State error feedback control law generates control signal u for system by using the error between the output of ESO and TD. The errors are combined in nonlinear manners; large errors is corresponding to lower gains, and small errors is corresponding to higher gains.

$$\begin{cases} e_1 = x_1 - z_1, \\ e_2 = x_2 - z_2. \end{cases}$$

where e_1, e_2 are the output errors. PID, as a control law, employs a linear combination of present, accumulative, and predictive forms of the tracking error and has, for a long time, ignored other possible combinations that are potentially much more effective. As an alternative, we propose the following nonlinear functions:

$$\mathrm{fal}(x, \alpha, \delta) = \begin{cases} \frac{x}{\delta^{1-\alpha}}, & |x| \leqslant \delta, \\ \mathrm{sgn}\, x|x|^{\alpha}, & |x| > \delta, \end{cases} \quad (5)$$

$$\mathrm{fhan}(x_1, x_2, r, h_0):$$
$$\begin{cases} d = rh_0^2, \\ a_0 = h_0 x_2, \\ y = x_1 + a_0, \\ a_1 = \sqrt{d(d+8|y|)}, \\ a_2 = a_0 + \mathrm{sgn}\, y \cdot (a_1 - d)/2, \\ s_{\mathrm{y}} = (\mathrm{sgn}(y+d) - \mathrm{sgn}(y-d))/2, \\ a = (a_0 + y - a_2)s_{\mathrm{y}} + a_2, \\ s_a = (\mathrm{sgn}(a+d) - \mathrm{sgn}(a-d))/2, \\ \mathrm{fhan} = -r(\frac{a}{d} - \mathrm{sgn}\, a)s_a - r\mathrm{sgn}\, a, \end{cases} \quad (6)$$

that sometimes provide surprisingly better results in practice. For example, with linear feedback, the tracking error, at best, approaches zero in infinite time; however, with nonlinear feedback of the form

$$u = |e|^{\alpha}\mathrm{sgn}\, e,$$

the error can reach zero much faster in finite time, with $\alpha < 1$. Such α can also help to reduce the steady-state error to the extent that an integral control, together with its downfalls, can be avoided. An extreme case is $\alpha = 0$, i.e, bang-bang control that can bring about zero steady-state error without the I term in PID. It is because of such efficacies and unique characteristics of nonlinear feedback to that we have given a systematic and experimental investigation. Such nonlinear feedback functions in the forms of fal and fhan play important roles in the newly proposed control framework. A nonlinear combination of error signal and its differential can be constructed as follows:

$$u_0 = k_1 \text{fal}(e_1, \alpha_1, \delta) + k_2 \text{fal}(e_2, \alpha_2, \delta),$$

where k_1 and k_2 are proportional and differential coefficients, respectively. The nonlinear function is used to make the observer more efficient. In order to achieve better performance, the nonlinear coefficient α_1 and α_2 are selected as $0 < \alpha_1 < 1 < \alpha_2$.

The controller is designed as

$$u = u_0 - \frac{z_3}{b_0}.$$

4 Practical application of ADRC

In this section, we will discuss the application of ADRC in different industrial control problems. We can see that ADRC plays an important part in the industry world.

4.1 Flight control

In this part, flight control for helicopters, spacecrafts and unmanned aerial vehicles will be discussed. In [38], ADRC is introduced in pitch and roll control to solve problems appeared in flight attitude control. In [39], a decoupling ADRC scheme for integrated flight-propulsion control (IFPC) is designed. Ref. [40] discusses the attitude control for a spacecraft model which is nonlinear in dynamics with inertia uncertainty and external disturbance. Ref. [41] discusses the problem of landing for unmanned aerial vehicles (UAVs) under various wind conditions. In [42] a novel nonlinear approach is proposed for high performance flight control design. The dynamic linearization is accomplished via extended state observer. Ref. [43] researches the problem of helicopter manoeuvres when the execution of the task can easily be affected by atmospheric disturbances.

4.2 Ship control

In this part, we will discuss ADRC used in ship course controller, ship tracking controller, ship main engine speed controller and ship straight-line tracking controller. Ref. [44] solves the problem of designing the ship tracking controller by utilizing ADRC method. Ref. [45] studies the ship course motion characteristics, gives the nonlinear model with disturbances and design an ADRC controller. In [46], a ship main engine optimal ADRC controller is designed for the mathematical model of nonlinear ship main engine under wave disturbances to the electronic governor with unmatched uncertainty. An active disturbance rejection nonlinear control strategy is proposed, and the genetic algorithm is used to modify parameters of ADRC online, which improves the ADRC's adaptive capacity. The simulation results show that the controller has good adaptive ability on the system nonlinearity and strong robustness to parameter perturbations of the ship and environmental disturbances. In [47], a straight-line tracking controller is designed for the non-linear and under-actuated mathematical model of ship's straight-line tracking control system based on ADRC technique.

4.3 Robot control

In this part, we will discuss the use of ADRC in robot control. Ref. [48] presents an ADRC law-based lateral control algorithm for tracking robots on stairs, with the heading angle estimated by the vision system installed on the robot. In [49], a second-order ADRC controller of the hydraulic system is designed. In [50], firstly, mobile robot (MR) lateral motion mathematical model is built and the ADRC design method is introduced. Then MR lateral motion system is regarded as a two-loop serial system, and its ADRC controller is designed. In [51], the extended state observer has been utilized for realizing the non-model-based cancellation of the nonlinear dynamics of the robot systems. In [52], the authors track the root strain signal by tracking-differentiator to obtain its differential signal, and take the two signals and its torsional signal gained by tip torsional gauge sensor as the nonlinear feedback input to control the vibrations of the flexible arms. Ref. [53] addresses the calibration-free robotic eye-hand coordination in a way different from the conventional image Jacobian matrix approach that has been studied extensively in literature.

4.4 Mission problem

Here, we will talk about the mission problem, including mission control and anti-control of missile electro-hydraulic actuator. In [54], an integrated guidance and control scheme is developed for the interception of maneuvering targets with the requested line-of-sight (LOS) angle based on the idea of ADRC. In [55], a novel approach combining the sliding mode control and ESO is proposed for attitude control of a missile model which is nonlinear in aerodynamics. Ref. [56] shows that spin is an effective way to penetrate laser's interception in the first boosting phase. Control couplings, motion couplings and other effects due to spin must be considered. Based on the principle of two time-scale separation of missile dynamics, a double-loop design method is applied to the roll channel, its attitude loop and damping loop uses respectively ADRC. In [57], ADRC technique is applied to the synthesis of a longitudinal autopilot for a missile with lateral thrust and aerodynamics involved. In [58], an advanced method of ADRC is presented aiming at the dynamics of the system that are highly nonlinear and have large extent of model uncertainties, such as tremendous changes in load.

4.5 Power plant

In this part, we will discuss the use of ADRC in power plant and some equipment. In [59], the real-time dynamic linearization is implemented by disturbance estimation via ESO and disturbance compensation via control law. Ref. [60] presents the development and application of an ADRC to regulate the frequency error for a three-area interconnected power system. Ref. [61] considers the difficulty of creating an accurate mathematical model for active power filter (APF), and takes ADRC as an alternate non-linear robust method. In [62], an ADRC for a power plant with a single loop is introduced for eliminating the shortcomings of the cascade PID control method. Ref. [63] presents the application of ADRC to an electrical power-assisted steering system (EPAS) in automobiles. Ref. [64] solves the problems, such as high current and torque ripple, associated with conventional PID control for brushless dc motor (BLDCM), and a new current controller based on fuzzy adaptive ADRC is proposed. In [65], an alternative framework is investigated to study the control problem in thermal power plants in which disturbance rejection is the central theme. In [66], a new control algorithm based on the active disturbance rejection concept is researched to cope with the highly nonlinear dynamics of the converter and the disturbances.

4.6 New energy

In this part, we will discuss the applications of ADRC in wind energy conversion systems and solar photovoltaic (PV) DC-DC converters. Ref. [67] shows that solar PV power generation system is a new type of solar energy of the electrical energy generating system. In [68], ADRC technology is applied to solar PV systems to control the DC-DC converter. In the system, model uncertainties and external disturbances are treated as an unified system of unknown interference. ESO is applied to dynamic observation of the disturbance, and the nonlinear state error feedback control law is used to compensate the system. So the control law is nothing to do with the parameters in the system and only unknown disturbance is with the system's given input and output. Ref. [69] summarizes the capturing methods for the largest wind energy, including the control of the tip speed ratio, mountaineering search method and three-points comparative method based on the mechanism of variable speed constant frequency (VSCF) wind turbine in capturing the largest wind.

4.7 Vehicle control

In this part, we discuss the applications of ADRC to vehicle control. Because of the uncertainties of the system model, it is difficult to control the automatic vehicle tracking the planned route. Different kinds of control methods have been used in it, such as the robust control, predictive control, slid moving control. Here we introduce ADRC in this field to solve the problem of uncertainties. Ref. [70] discusses the lateral locomotion control. Lateral locomotion control is an important technology for intelligent vehicles and intelligent transportation system (ITS), and it is significant to vehicle active safety. In [71] the control method for the anti-lock braking system (ABS) with regenerative braking of electric vehicles is studied. Control of regenerative retarding of a vehicle equipped with a new energy recovery retarder is discussed in [72]. Ref. [73] mainly discusses maglev train. Based on practical requirement, the dynamics model of maglev train is built. An ADRC control algorithm for train automatic operation system is proposed to substitute the traditional PID control algorithm.

4.8 Gyroscope

Here, we introduce the use of ADRC in different kind of gyroscopes. In [74], a new control method is presented to drive the drive axis of a micro-electro-mechanical systems (MEMS) gyroscope to resonance and to regulate the output amplitude of the axis to a fixed level. Ref. [75] presents the ADRC algorithm based on the typical structure of two-axes and four-frames. Ref. [76] presents a novel oscillation controller for controlling the driving mode (or drive axis) of a vibrational gyroscope to oscillate at a desired trajectory. The controller consists of a PD controller and an on-line ESO. Ref. [77] demonstrates how a novel active disturbance rejection control addresses these problems in the presence of the mismatch of natural frequencies between two axes, mechanical-thermal noises, quadrature errors, and parameter variations. Ref. [78] presents a novel control circuitry design for both vibrating axes (drive and sense) of vibrational gyroscopes, and a new sensing method.

4.9 Motion control

In this part, we will introduce the applications of ADRC in motion control. Ref. [79] presents the detailed results from total of 168 tests performed on the state of the art PLC and drives, characterizing the performance of both the existing industry controller and ADRC. In [80], a new control solution to motion control problems is proposed. It is through VSC based on ESO, where the disturbances and high-order factors are estimated and compensated using ESO. A new digital control solution to motion control problems is proposed in [81]. It is based on a unique active disturbance rejection concept, where the disturbances are estimated using ESO and compensated in each sampling period. Ref. [82] solves a particular motion control problem that is how to select the most appropriate control law and its parameters. The controllers for selection include the conventional PID control and its variations, the parameterized loop-shaping method, as well as the more recent linear active disturbance rejection method.

4.10 Motor control

Here, we will show some examples of using ADRC in motor control. From these practical application, we can see the benefit of ADRC in disturbance rejection and robustness performance in comparison with other control method. Ref. [83] puts forward a novel position controller based on ADRC theory to ensure high dynamic performance of magnet synchronous motor (PMSM) servo system. In [84], a novel approach to position sensorless vector control system of permanent magnet synchronous motor (PMSM) based on ADRC is presented. In [85], a nonlinear ADRC has been developed to ensure high dynamic performance of induction motors in this paper. In [86], a highly robust ADRC is developed to implement high-precision motion control of permanent-magnet synchronous motors.

4.11 Servo system control

The industrial machines are an important part of the world industry. In order to improve the precision, energy-saving, we need to develop an effective servo system. Many different strategies have been introduced here, such as, increment PI control, fuzzy PID control, neural PID control, multi-segment PI control. Here we mainly talk about servo systems based on ADRC strategy. As we know that permanent magnet synchronous motor (PMSM) servo drive system has been widely used in industrial sewing machines. In [87], a servo control of the industrial sewing machine system based on ADRC theory is introduced to substitute the conventional PID method which has some disadvantages such as large overshoot, bad robustness. Ref. [88] discusses the application of ADRC to tracking control of a fast tool servo system. Ref. [89] discusses a design method of ADRC for linear motor servo system.

4.12 Other applications

Besides this, here we will introduce the use of ADRC in other parts of the industry world. In [90], a new dynamic decoupling method is proposed for controlling complex uncertain systems, where mathematical modeling is often tedious or inaccurate, the new method uses an unknown input observer (UIO) to estimate and cancel dynamic information in real-time. In [91], a fundamental and open issue pertaining to human postural sway is how to deal with the uncertain, nonlinear and time-varying nature of human motor dynamics. To address the inherent limitations of the current methods, such as PID and model-based designs, a novel active disturbance rejection concept is introduced. In [92], a novel application, employing the strategy of ADRC and ESO, is proposed to control the rotor shaft position of national aeronautics and space administration (NASA) high speed shaft (HSS) flywheel using active magnetic bearings. In [93], ADRC is proposed whereby the hysteresis with unknown characteristics is treated as disturbance and rejected. In [94], a new control method is proposed for tension regulation in a web transport system. It is based on a unique ADRC strategy which actively compensates for dynamic changes in the system, and unpredictable external disturbances. Simulation results show the effectiveness of the proposed tension controller in coping with large dynamic variations commonly seen in web tension applications. The remarkable disturbance rejection capability of ADRC is also demonstrated. In [95], a novel control strategy, ADRC, is applied to the representative process control problems. In the ADRC framework, the disturbance and unmeasured dynamics associated with chemical processes are treated as an additional state variable, which is then estimated and compensated for in real-time. This reduces a normally complex, time-varying, nonlinear, and uncertain dynamic process to an approximately linear, time-invariant, cascade-integral form, where a simple proportional-derivative (PD) controller suffices. Ref. [66] presents the design and implementation of an advanced digital controller for a 1-kWH-bridge DC-DC power converter. A new control algorithm based on the active disturbance rejection concept is developed to cope with the highly nonlinear dynamics of the converter and the disturbances. An experimental digital control system is used to implement the new control strategy. In [96], a field programmable gate array (FPGA)-based digital control and communication module (DCCM), designed to be the backbone for future space power management (PMAD) systems, is developed and implemented. In that paper, the hardware architecture and logic design of the module are addressed. ADRC has been applied to solve various types of control problems across many engineering disciplines, but largely within the scope of minimum phase systems. Ref. [97] explores systematically its applications to non-minimum phase (NMP) systems, particularly those with transfer functions that have right half plane zeros. It is first shown that a regular ADRC controller, if not tuned carefully, could easily yield an undesirable solution for NMP systems. In [98], a unique disturbance rejection control strategy is proposed for a class of tension and velocity regulation problems found in web process lines. The proposed control system actively estimates and rejects the effects of both dynamic changes in the system and external disturbances. Both open-loop and closed-loop tension regulation schemes are investigated.

Ref. [99] presents a method for active disturbance rejection in the antenna pointing control of a large flexible satellite system. A simplified dynamic model is established using Euler-Lagrange equation and used to analyze the dynamic stability of the antenna system. The capturing strategy of the antenna is configured and the inner and outer loops of the ADRC are then designed to improve pointing accuracy and rotation speed. The design of the ADRC is verified through numerical simulation. Ref. [100] presents a linear active disturbance rejection controller design for a voice coil motor-driven fast tool servo system for noncircular machining application.

5 Brief introduction of disturbance observer/differentiator

The disturbance observer (DO) which has been developed in [26, 101–102] has the high efficiency in accomplishing the nonlinear dynamic estimation. Therefore, in order to solve the attitude tracking problem with inertial uncertainties and disturbances existing in the spacecraft system, we design a sliding mode controller to force the state variables to converge to the reference state by totally compensating the disturbances by means of the disturbance observer (DO) proposed in [26, 101–104]. In [24, 101], a universal finite-time-convergent controller is developed capable to control the output of any uncertain single-input-single-output system. It is noted that the controller dependents only on $\sigma, \dot{\sigma}, \cdots, \sigma^{(r-1)}$ and requires the real-time exact calculation or direct measurement of σ, $\dot{\sigma}$, $\cdots$, $\sigma^{(r-1)}$. In [105], the quasi-continuous second- and third-order sliding controllers and differentiators have been successfully applied to spacecraft-attitude-tracking maneuvers. In [26, 102], a smooth 2-sliding control disturbance observer is employed. $g(t)$ is the disturbance and is $m-1$ times differentiable.

6 Brief introduction of compound control

However, SMC will suffer from chattering which may bring about poor performance, and the uncertainties and disturbances can not be observed by ESO perfectly, especially when the uncertainties and disturbances are beyond the observability of ESO, they can not be compensated completely by ADRC. Compound control composes advantages of SMC and ADRC, it consists of two steps: I) When the trajectory of controlled systems is far away from the equilibrium, SMC is applied; and II) When the trajectory is near equilibrium, ADRC is adopted. In [106], the sliding mode surface is designed as $S = x$, with some simple algebraic manipulations, the spacecraft systems are simplified as

$$\dot{x} = F + B_0 u + \tilde{d}, \tag{7}$$

where $\tilde{d}$ is the total uncertainties including inertia uncertainties and external disturbances. Then a second-order ESO for system (7) is proposed in the following:

$$\begin{cases} E_1 = Z_1 - x, \\ \dot{Z}_1 = Z_2 + F - \beta_{01} E_1 + B_0 u, \\ \dot{Z}_2 = -\beta_{02} \mathrm{fal}(E_1, \alpha_1, \delta), \end{cases} \tag{8}$$

where E_1 is the estimation error of ESO, Z_1 and Z_2 are the observer outputs, and β_{01}, β_{02} are the observer gains. Therefore, the performance of compound control is significant, the detailed description can be found in [106], which is shown in Fig.4. If inertia uncertainties ΔJ and external disturbances d are all differentiable, the second-order differentiator for the estimate of the total disturbances $\tilde{d}$ takes the form[107]

$$\begin{aligned}
&\dot{z}_0 = v_0 + B_0 u + F, \\
&v_0 = -\lambda_0 \begin{pmatrix} L_{01} & 0 & 0 \\ 0 & L_{02} & 0 \\ 0 & 0 & L_{03} \end{pmatrix} \begin{pmatrix} \mathrm{sgn}(z_{01} - \tilde{S}_1) \\ \mathrm{sgn}(z_{02} - \tilde{S}_2) \\ \mathrm{sgn}(z_{03} - \tilde{S}_3) \end{pmatrix} + z_1, \\
&\dot{z}_1 = v_1, \\
&v_1 = -\lambda_1 \begin{pmatrix} L_{11} & 0 & 0 \\ 0 & L_{12} & 0 \\ 0 & 0 & L_{13} \end{pmatrix} \begin{pmatrix} \mathrm{sgn}(z_{11} - v_{01}) \\ \mathrm{sgn}(z_{12} - v_{02}) \\ \mathrm{sgn}(z_{13} - v_{03}) \end{pmatrix} + z_2, \\
&\dot{z}_2 = -\lambda_2 L \begin{pmatrix} \mathrm{sgn}(z_{21} - v_{11}) \\ \mathrm{sgn}(z_{22} - v_{12}) \\ \mathrm{sgn}(z_{23} - v_{13}) \end{pmatrix},
\end{aligned}$$

where $L_{01} = L_1^{1/3} \cdot |z_{01} - \tilde{S}_1|^{2/3}$, $L_{02} = L_2^{1/3} \cdot |z_{02} - \tilde{S}_2|^{2/3}$, $L_{03} = L_3^{1/3} \cdot |z_{03} - \tilde{S}_3|^{2/3}$, $L_{11} = L_1^{1/2} \cdot |z_{11} - v_{01}|^{2/3}$, $L_{12} = L_2^{1/2} \cdot |z_{12} - v_{02}|^{2/3}$, $L_{13} = L_3^{1/2} \cdot |z_{13} - v_{03}|^{2/3}$. $z_i, i = 0, 1, 2$ are the estimates of $\tilde{S}$, $\tilde{d}$, and $\dot{\tilde{d}}$, respectively, $L_i \geqslant \| \ddot{\tilde{d}}_i \|, i = 1, 2, 3$, and $L = \mathrm{diag}\{L_1, L_2, L_3\}$. The benefits of modified differentiator (MD) are that the asymptotic stability can be analyzed and only one parameter L in MD should be adjusted. The drawback of MD is that only the differentiable disturbances and uncertainties can be estimated. This detailed analysis can be found in [107].

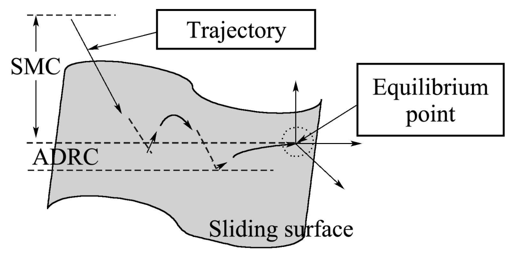

Fig. 4 Compound control

Certainly, other modern control theories are applied as well, they are also parts of compound control according to the characters of uncertainties and disturbances. For example, SMC based on Delta operator can also give good performance[108]. Therefore, compound control methodology is proposed for flight vehicle control, which is of great importance[13,55,109].

7 Conclusions

Compound control has been introduced in this paper, which can overcome the limiations of SMC and ADRC, and improve the performance of the closed-loop system. However, there are still fruitful results which need to be investigated in the future.

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