EXTENDED ABSTRACT

An overview of the active disturbance rejection control (ADRC) is presented in this talk. Ever since ADRC was proposed by Jingqing Han in 1990s[1], it has become quite an attractive methodology to applied researchers, even though rigorous theoretical justification was lagging behind for quite some time. The fact that ADRC possesses certain uniqueness in concepts, simplicity in engineering implementation, and superior actual performance allowed it to be readily translated into a valuable asset in engineering practice: namely, the ability in dealing with a vast range of uncertainties, improved transient response, easy implementation and energy savings, to name but a few. The range of applications seems broad, covering almost all domains of control engineering, such as motion control, speed control of induction motor and permanent-magnet synchronous motor, control for noncircular turning process, low-velocity compensation of brushless DC servo, robotic system, underactuated mechanical systems, micro-electro-mechanical systems gyroscope, control for superconducting RF cavities, flight control, attitude tracking of rigid spacecraft, web tension regulation, DC-DC power converter, chemical processes, ALSTOM gasifier benchmark problem, the boiler-turbine-generator control systems, stabilization of axial flow compressors, the fractional-order system, etc. [10]-[31]. In the U.S.A., the ADRC solution was recently deployed at a Parker Hannifin Extrusion Plant in North America, resulting in over 50% energy saving per line across ten production lines, together with significant improvements in product quality [32]. And Texas Instrument has adopted the ADRC technology in developing and distributing a new line of motion control chips worldwide [33]. The National Superconducting Cyclotron Lab in the U.S. has implemented ADRC in several high energy particle accelerators after significant improvements have been obtained in amplitude and phase regulation of electromagnetic fields. The talk aims to provide the audience with an understanding of the principles behind the success of ADRC and to address questions such as: What’s unique about the concept of ADRC? What characterizes the ADRC as a viable technology? And what to expect in the future regarding the technological expansion and the continuous generation of ideas?

Principles and Methods

What is ADRC? ADRC can be described from different points of view:

- **Active disturbance rejection control (ADRC)** can be summarized as follows: it inherits from proportional-integral-derivative (PID) the quality that makes it such a success: the error driven, rather than model-based, control law; it takes from modern control theory its best offering: the state observer; it embraces the power of nonlinear feedback and puts it to full use; it is a useful digital control technology developed out of an experimental platform rooted in computer simulations. (-Han J. From PID to Active Disturbance Rejection Control,IEEE Trans. Ind. Electron., 56(3), 900-906(2009)).

- **ADRC** is but an advanced form of PAC (principle of active control) where the physical process is idealized in the form of cascaded-integrators, based on which the controller is designed; the discrepancy between the actual plant and its ideal form, as a function of both internal dynamics and external disturbances, is treated as a total disturbance and is then estimated and cancelled out. (-Gao Z. On the conceptualization of automation control,Proceedings of the 32nd Chinese Control Conference, 199-204(2013)).

- This new area of research is known as active disturbance rejection control (ADRC), with the disturbance referring to both internal (state dependent) and external forces that are unknown. The work of Han demonstrates that many boundaries in control theory are artificial, reflecting not the nature of automatic control but our limitations in comprehending it. Such boundaries include those that divide the systems as linear and nonlinear control, internal dynamic uncertainty and external disturbance, time varying and time invariance, etc. In fact, all these problems can be seen as one and the same: the problem of disturbance, if the word disturbance is allowed to take on the more general meaning described above. (-Gao Z. On the centrality of disturbance rejection in automatic control,ISA...
To let the audience get their own answers, the unique ideas to promote the development of ADRC and the key in employing ADRC are first illuminated.

ADRC is developed mainly based on Han’s two fundamental breakthroughs:

1) the canonical form that transcends the boundary of linear and nonlinear systems, which was presented at the 1st Chinese Control Conference in 1979[2].

2) the concept of extended state or total disturbance that accounts for various uncertainties both internal and external to the plant dynamics, which was proposed in 1990s[5],[1].

The foundation of ADRC rests on the two best offerings of modern control theory: the idea of canonical form and that of state observer.

The basic idea of ADRC is quite straightforward:

1) select the canonical form of the plant in the form of cascade integrators;

2) treat the part of plant that is different from this canonical form as the "total disturbance", which may include the external disturbance from the environment and the internal disturbance, a term coined by Han, representing the uncertainties and variations in the dynamics of the plant;

3) reduce the system, which may be uncertain, nonlinear, coupled with other process variables, and time varying, to the canonical form by means of estimating and compensating for the "total disturbance" via a special observer conceived by Han, the extended state observer (ESO).

In this talk, the key in employing ADRC, which is to accurately determine the "total disturbance" that affects the output of the system, is illuminated by several examples, such as the systems with unmatched uncertainties and the underactuated uncertain systems.

Unmodeled dynamics, parametric variations as well as external disturbances widely exist in most engineering systems. This is one of the main reasons why disturbance rejection or control of systems with uncertainty is the most fundamental issue in control science. Substantial efforts have been made and much progress has been achieved, such as adaptive control, robust control, disturbance observer based control (DOBC), sliding-mode control, model-free control, Embedded Model Control, etc.[36]-[54]. The breakthroughs in the investigation of uncertain systems, made possible by ADRC, are discussed in the talk.

Moreover, we believe by clearing the kernel of ADRC, more innovations can be inspired to improve ADRC. For example, ADRC connected to flatness in determining an input-output model of the system (mono or multivariable) brings new solutions for control of nonlinear uncertain systems. The approach is devoid of matching conditions requirements and zero dynamics problems. Furthermore, it is only based on measurement of the flat output, which is nearly always a physically significant output[55].

## Practice

ADRC provides the possibility for overcoming the difficulty of controlling uncertain systems. However, the grand and ambitious scheme of ADRC met with some doubts when it was proposed: is it really able to handle the vastly uncertain nonlinear systems in practice? Is its way of rejecting the "total disturbance" too crude for high precision control? Is there any theoretical basis for this idea?

Though theoretical justification was lagging behind for quite some time, ADRC has become quite attractive to applied researchers. Much applied research has been carried out by many research groups across the globe in a diverse range of engineering disciplines. [10]-[33] are a few samples.

In the high-precision machining process, the experimental results for noncircular turning process (NCTP) demonstrated the effectiveness of ADRC with tracking errors being reduced to less than 3 μm for different cutting parameters. Moreover, Texas Instrument (TI) has adopted the ADRC technology in developing and distributing a new line of motion control chips worldwide.

In the flight control problem, thousands of simulation tests on different kinds of aircrafts along with the successful experiments for attitude control have convincingly shown that ADRC can achieve effective control of a complex system in the absence of a detailed and accurate mathematical model.

The experiments on the high-precision machining process, the test of TI’s SpinTACTM MOTION Control Suite, and the applied research on flight control will be shown in the talk. The applied researches in the ADRC groups around the world will also be briefly introduced.

## Analysis

The research on the theoretical analysis for ADRC was progressing haltingly amid great difficulties, which can be traced to the nature of ADRC. The uncertain systems of concern are allowed to be nonlinear, time-varying, multi-input and multi-output; the disturbance signal or the reference signal may not even be continuous; and the state feedback in ADRC is, in general, nonlinear. Such great ambition is equally matched by the great challenge in theoretical analysis for the purpose of explaining and justifying the engineering success: how to rigorously find the capacity of ADRC in dealing with vastly uncertain nonlinear systems? How to rationalize the outstanding performance in the presence of large uncertainties shown in numerous applied researches? What are the limits on the scope of applications for ADRC?

In recent years, stimulated by increasingly successful applied researches of ADRC, the theoretical research has been gradually set in motion, targeting first various components of ADRC, such as the tracking-differentiator (TD)[56]-[59] and the extended-state observer (ESO)[60]-[64], eventually arriving at, finally, the property of the entire ADRC-based closed-loop system[65]-[75].

TD was first proposed in [4] in the general nonlinear form to provide the filtered version of the input signal and its differentiation. Unfortunately, the proof in [4] was incomplete. In recent years, further analysis on the convergence of TD have been obtained. In [57], the convergence was proved for a second order linear TD with any differentiable
input signal and random perturbation. [58] surveyed several kinds of differentiators. The comparison showed that TD permits a weaker condition on the stability of the systems, which can be used to construct differentiators. Moreover, T-D sets weaker constraints on the input signal. The proofs for two kinds of nonlinear TD were also given in [58]. In [59], a rigorous proof of the convergence was given for the nonlinear TD under some additional assumptions. By now, the analysis on TD mainly emphasizes the convergence. Further study on its advantages in anti-chattering and noise tolerance is still to come.

Since the “total disturbance” to be estimated by ESO may be a function of both the state, the disturbance and the control signal, the analysis on ESO is intricately connected with that on the ADRC-based closed-loop systems in which it is used.

Remark 1. ESO can also be used separately from any control loops, in which case the signals it estimates can be assumed bounded. In this case, ESO functions as a filter or differentiator and it should be analyzed as such. The research is still in its early stage.

The theoretical analysis on ADRC has been carried out from several different perspectives.

To render the idea clear and the controller easy to implement and to tune, a parameterized linear ADRC (LADRC) was proposed in [76], where nonlinear gains are replaced with linear ones and tuning is reduced to the adjustment of one variable, the bandwidth, which is the common terminology used by engineers. LADRC has already shown great promise in many areas of control engineering. The capability of LADRC has been analyzed.

In [65]-[66], the analysis results in the frequency-domain were shown. In [65], the loop gain frequency response was analyzed for a second-order linear time-invariant plant. The result showed that the LADRC based control system possesses a high level of robustness. The bandwidth and stability margins, in particular, are nearly unchanged as the plant parameters vary significantly; so is the sensitivity to the input disturbance. Such characteristics explain why LADRC is an appealing solution in dealing with real world control problems where uncertainties abound. [66] further investigated the frequency properties of LADRC with the reduced-order LESO for a typical class of n-th order linear time-invariant uncertain system. It was shown that the phase margin and crossover frequency are almost unchanged in the presence of some uncertain parameters. And moreover, different kinds of uncertain parameters have various influences on the robustness of the ADRC based control system. In [67], the capability of LADRC for linear time-invariant SISO minimum-phase systems with unknown but bounded relative degrees, and unknown input disturbances, was analyzed. The result explains why one ADRC with fixed parameters can be applied to a group of plants of different orders, relative degrees, and parameters.

Vast successful applied research also revealed the capability of LADRC for nonlinear uncertain systems. In [68], the stability of the closed-loop system under LADRC was studied with the assumption that the “total disturbance” to be estimated and compensated for is bounded. Since the “total disturbance” to be estimated by ESO may be a function of both the closed-loop state, the disturbance and the real control input, the boundedness of the “total disturbance” is hard to be estimated in advance. Because of the similarity between LESO and the observers in [77]-[79], these literatures provided some enlightening results for the analysis of ADRC, particularly in relaxing the assumption on the boundedness of the “total disturbance” and analyzing the performance recovery of the closed-loop system. [69],[70] and [71] further discussed the transient performance and the stability of LADRC design for nonlinear uncertain systems in the cases of SISO systems, discontinuous disturbance and MIMO block lower-triangular systems, respectively. Furthermore, the idea of LADRC has been employed to stabilize some classes of the infinite-dimension systems with external disturbance[72]-[73].

The parameters of LADRC, implemented digitally, are restricted by the sampling rate. [74] studied the parameters tuning and the capability of LADRC under a fixed sampling rate. The quantitative relationship among the parameters of LADRC, the sampling rate and the uncertainty to be dealt with was given.

The original form of ADRC is a much more general nonlinear controller. The theoretical analysis of the nonlinear ADRC (NADRC) is quite difficult. [62] and [75] opened the theoretical analysis of nonlinear ESO(NESO) and NADRC for nonlinear time-varying uncertain systems. The convergence of NADRC was proved for a class of MIMO nonlinear systems with large uncertainty that comes from both dynamical modeling and external disturbance[75].

The high level of robustness and the superior transient performance are the most valuable characteristics of ADRC making it be an appealing solution in dealing with real world control problems. The main results of [66] and [70], which can explain these characteristics from the views of the frequency-domain and the time-domain respectively, will be introduced in details in the talk.

Remark 2. The theoretical analysis of ADRC has been well developed for vast kinds of uncertain systems and from various views. The details of the related theoretical work can be obtained from the references and those therein.

Although the theoretical research of ADRC has been developed from different angles, the research is still in its early stage. Many challenging theoretical problems remain unresolved. An exposition of open research problems for interested members of the audience will also be presented in the talk.

In conclusion, ADRC represents a new set of principles, methods, engineering tools, and a great challenge in building a sound theoretical basis. We hope such challenges will lead to ever more exhilarating research in the future!

Key Words

Active disturbance rejection control (ADRC), nonlinear uncertain system, disturbance rejection

References


[9] Huang Y. Xue Wenchao. Active disturbance rejection control: methodology and theoretical analysis, ISA Transaction, http://dx.doi.org/10.1016/j.isatra.2014.03.003


[44] Francis B.A., Wonham W.M. The internal model principle of


