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Review

Active Disturbance Rejection Control for Piezoelectric Smart Structures: A Review

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Abstract: The piezoelectric smart structures, which can be labeled as the cream of the crop of smart structures without overstatement, are strongly impacted by a large number of uncertainties and disturbances during operation. The present paper reviews active disturbance rejection control (ADRC) technologies developed for application in piezoelectric smart structures, focusing on measurement, analysis, estimation, and attenuation of uncertainties/disturbances in systems. It first explained vast categories of uncertainties/disturbances with their adverse influences. Then, after a brief introduction to the application of basic ADRC in smart structures, a thorough review of recently modified forms of ADRC is analyzed and classified in terms of their improvement objectives and structural characteristics. The universal advantages of ADRC in dealing with uncertainties and its improvement on the particularity of smart structures show its broad application prospects. These improved ADRC methods are reviewed by classifying them as modified ADRC for specific problems, modified ADRC by nonlinear functions, composite control based on ADRC, and ADRC based on other models. In addition, the application of other types of active anti-disturbances technologies in smart structures is reviewed to expand horizons. The main features of this review paper are summarized as follows: (1) it can provide profound understanding and flexible approaches for researchers and practitioners in designing ADRC in the field and (2) light up future directions and unsolved problems.

Keywords: active disturbance rejection control (ADRC); piezoelectric smart structures; vibration control; uncertainties and disturbances

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1. Introduction

The requirements for structural reliability, economy, and comfort in engineering are growing at an unrelenting pace. However, the traditional structures designed according to certain dynamic requirements, when facing changes in the external environment, struggle to make appropriate adjustments. Vibration and the resulting noise and fatigue problems restrict the development of extensive facilities in various industries. The emergence of smart structures provides an ideal solution for structural vibration suppression, which integrates sensors, actuators, and controllers into the matrix material, making it have intelligent functions such as self-diagnosis, and self-healing [1]. As a prominent smart material currently available, piezoelectric materials have the following advantages:

- Small size and light weight;
- Wide applicable frequency band;
- High electromechanical conversion efficiency;
- ...

Active vibration control based on piezoelectric smart structures has great application prospects. In the field of aerospace, piezoelectric elements can reduce the harmful vibration of the system [2–4]. In civil engineering, piezoelectric components can monitor structural health in real time, including bolt looseness, grouting density, and so on [5]. In addition, piezoelectric materials are also widely used in automobiles, architecture medical fields, airflow, and other fields [1,6–9].

The active control strategy based on the combination of piezoelectric smart structures and control theory can accurately control the vibration in the face of a severe mechanical environment. The negative velocity feedback control, PID controller, and linear quadratic regulator (LQR) are the most commonly used control laws because of their simple structure and easy implementation [10–12]. However, traditional methods are not efficient enough and lack robustness. For example, it is difficult for LQR to obtain satisfactory control performance for structures with uncertain structural parameters and external disturbances. Unfortunately, a large number of uncertainties and disturbances including higher harmonics, diversity of boundary conditions, and uncertain external excitations inevitably exist. Therefore, in order to improve the control performance, the vibration suppression strategy of a closed-loop system with strong robustness is attempted to be studied and designed, such as adaptive control, sliding mode control and so on [13–15]. In addition to feedback control, an ideal way to deal with disturbances is to introduce a feedforward mechanism to eliminate the disturbances. The limitation is that disturbances are generally unmeasurable. To this end, several disturbance estimation technologies are investigated to estimate the disturbance of the system [16–18]. All in all, with the increasing requirements for structural reliability, economy, and comfort, this challenging and critical problem has forced both piezoelectric smart structures and control communities to design adequate controllers providing satisfactory performance as well as a simple structure to achieve vibration suppression performance for smart structures subjected to various disturbances.

The active disturbance rejection control (ADRC), first proposed by Han, is a possible solution to the aforementioned problems, due to its simple structure, partial model dependence, and good control performance [19]. The ADRC based on the extended state observer (ESO) uniquely summarizes the internal uncertainties and unknown external disturbances of the system into the "total disturbances" and extends the total disturbances to a state of the system. The real-time estimation of total disturbance is conducted by ESO and compensated via the feedforward channel. Because ADRC does not depend on the accurate mathematical model of the system and uncertainties, the influence of the internal and external disturbances is reduced to the total disturbances. It uses the classical error feedback idea to estimate it in real time and give feedforward compensation, which has strong robustness. ADRC has no specific mathematical form to limit uncertainty and can control time delay systems, multivariable coupling systems, etc. It is a very practical control method and has been successfully applied in many fields, such as aerospace, power electronics, and servo control [20–22]. Fareh et al. provided a comprehensive review of various ADRC frameworks designed for robotic systems [23]. Chen et al. gave a comprehensive assessment of various modified ADRC frameworks for time delay systems [24]. ADRC techniques for the control of non-minimum phase DC/DC boost converters are reviewed in [25]. Wu et al. reviewed the development of ADRC theory and its application in the infinite-dimensional problem [26].

In recent years, ADRC has been applied in piezoelectric smart structures applications, and gradually emerged many related research works have been published. In order to provide a profound understanding for practitioners and light up future directions which may inspire more innovations, it is necessary to summarize the existing results. In particular, how to understand the total disturbances of piezoelectric smart structures under the ADRC framework, how to establish control models, and how to deal with intractable dynamics such as hysteresis, control–structure interaction, and time delay. This paper will demonstrate a comprehensive review of the application and implementation of the ADRC approach in piezoelectric smart structures.

We have based our review on recent papers. Firstly, the modeling of piezoelectric smart structures is introduced, in which a dynamic finite element model of smart structures is derived, and piezoelectric modal sensors are also introduced. Then, the disturbances and uncertainties in smart structures are elaborated on in detail. Sections 3 and 4 present the theoretical foundation and formulation of the ADRC for piezoelectric smart structures. Applications of the modified ADRC approach are discussed in categories, including applications of composite control based on ADRC, the nonlinear ADRC strategy, etc. Some other active anti-disturbance control methods are provided in Section 5. Finally, the conclusion is given in Section 6.

2. Disturbance Sources of Piezoelectric Smart Structures

2.1. System Modeling

With modern control theory as the primary tool, vibration control based on piezoelectric smart structures uses piezoelectric elements as actuators and sensors. According to the direct piezoelectric effect, the piezoelectric sensor obtains the physical quantity of the structure vibration, converts it into the corresponding electrical signal, and obtains the corresponding control signal through the set control law, which is applied to the piezoelectric actuator after the power amplifier. According to the inverse piezoelectric effect, the actuator converts the electrical energy into mechanical energy, so as to achieve structural vibration suppression.

Although the active control method based on ADRC strategy does not depend on the accurate modeling of the structure, in order to improve the vibration suppression performance of the system and the theoretical analysis of the stability of the control system, the mathematical model of the intelligent structure is needed. By literature review, it reveals that most studies developed conventional control laws based on linear finite element (FE) models. Therefore, disturbance rejection control is developed based on linear FE models.

2.1.1. Constitutive Equations

Due to the assumption of a weak electric field and small strain, the constitutive equations of a general piezoelectric material can be constructed as [27]:

$$T_{ij} = c^{E}_{ijkl} S_{kl} - e_{kij} E_k \tag{1}$$

$$D_i = e_{ikl} S_{kl} + \varepsilon^{S}_{ik} E_k \tag{2}$$

where T_{ij}, S_{kl}, E_k, and D_i are, respectively, the components of the stress, strain tensors, the electric field vector, and the electric displacement vector. c^{E}_{ijkl} are the elastic constants, e_{kij} the piezoelectric constants, and ε^{S}_{ik} the dielectric constant under constant strain. Where all indices i, j, k, l = 1, 2, 3, and there is a summation on all repeated indices. The relationship between the electrical properties and mechanical properties of piezoelectric materials is reflected by the piezoelectric equation.

2.1.2. Electromechanical Coupling Model

Plate structures are the most common lightweight structures, and also the typical type of smart structures considered in this paper. According to Hamilton's principle and finite element method, the electromechanical model of smart structures is obtained as [17,28]:

$$\mathbf{M}_{uu}\ddot{\mathbf{q}} + \mathbf{C}_{uu}\dot{\mathbf{q}} + \mathbf{K}_{uu}\mathbf{q} + \mathbf{K}_{u\phi}\phi_a = \mathbf{f} \tag{3}$$

where matrices $\mathbf{M}_{uu}$, $\mathbf{C}_{uu}$, $\mathbf{K}_{uu}$, and $\mathbf{K}_{u\phi}$ denote the mass matrix, the damping matrix, the stiffness matrix, and the piezoelectric coupled stiffness matrix, respectively. Vectors $\mathbf{q}$, ϕ_a, and $\mathbf{f}$ represent the nodal displacement vector, the actuation voltage vector, and the external force vector, respectively. The motion of a dynamic system can be described by the linear combination of the main modes. Therefore, using the orthogonality theory of the array normalization, the dynamic equation of the n-th mode is further simplified as:

$$\ddot{\eta}_n + 2\zeta_n\omega_n\dot{\eta}_n + \omega_n^2\eta_n = f_n + b_n u \tag{4}$$

where η_n is modal coordinates. The parameters ω_n and ζ_n are natural angular frequency and damping of the n-th mode, respectively. f_n, b_n, and u denote the external modal excitation force after change, control gain, and the control voltage.

Equations (1) and (2) show the characteristics of piezoelectric elements. Equation (3) is the dynamic equation of a smart structure composed of a piezoelectric actuator and structure. Equation (4) is the discretization of Equation (3) by using the mode shape function, and it is also the model in the upcoming derivation of the ADRC control scheme.

2.2. Disturbances/Uncertainties in Smart Structures

The real smart structure system, as opposed to its simplified model, is a challenging control problem as it consists of multiple sources of disturbances/uncertainties. They are classified and briefly described as shown in the following Figure 1 and Table 1.

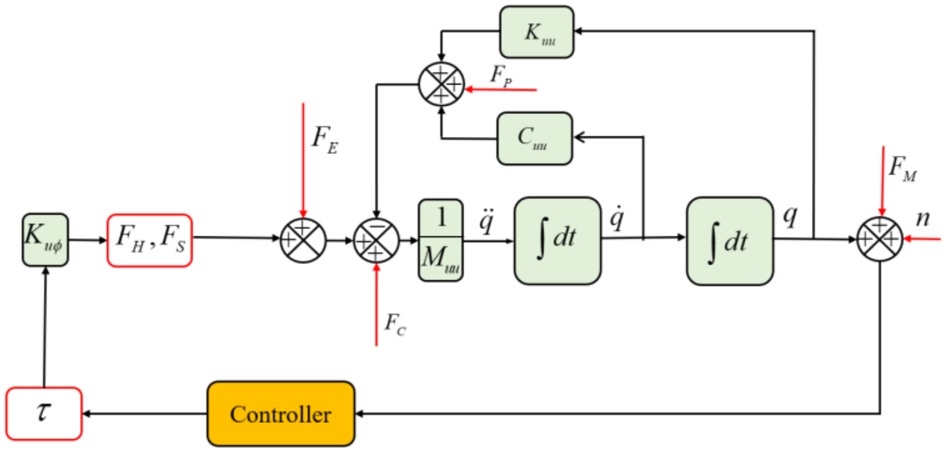

Figure 1. Distribution of disturbance/uncertainty in piezoelectric smart structures.

Table 1. Disturbances/Uncertainties in smart structures.

Symbol	Meaning
Δ	Nonlinear dynamics of structures
F_H	Hysteresis property of piezoelectric actuator
F_S	Saturation nonlinearity
F_P	Parametric uncertainties
F_C	Control–structure interaction
F_M	Measurement error effects
n	Measurement noise
τ	Time delay
F_E	External disturbances

The dynamics of smart structures are essentially nonlinear subject to a wide range of disturbances/uncertainties in many high-performance applications. In this section, the disturbances/uncertainties in smart structures systems, which are classified as unmodelled dynamics, parametric uncertainties, control–structure interaction, measurement error effects, and external disturbances, are briefly reviewed first.

2.2.1. Unmodeled Dynamics

In order to facilitate the design and analysis of the controller, the linear model based on the finite element method is simplified, which cannot reflect the nonlinear and time-varying characteristics of the system. In practice, when the controller operates, unmodeled dynamics may result in undesirable interactions. In the sequel, several nonlinear characteristics of smart structures are summarized.

(1) Nonlinear dynamics of structures: Some review literature on the recent development of modeling techniques for smart structures can be founded in [29–31]. One challenge is the precise prediction of the structural response for smart structures undergoing small/large displacement, under weak/strong electric fields, or for various piezoelectric materials. The design of the control method based on a linear model does not take into account the nonlinearity, however, smart systems have nonlinear dynamics [32,33]. At the same time, the acquisition of the linear model is also based on some assumptions, such as the piezoelectric effect on the piezoelectric actuator when the structure deformation is not considered.

(2) Hysteresis property of piezoelectric actuator: The piezoelectric actuator (PZA) plays an essential role in the smart structure. Nevertheless, as a constituent component, hysteresis nonlinearities are displayed on PZA, which may bring about severe degradation of system performance [34]. For the sake of the inhibition of the hysteretic property, the literature concentrating on modeling technology continues to emerge. The mathematical models fall into two categories: phenomenal models and physical models [35]. The Prandtl–Ishlinskii model, which can well describe rate-independent hysteresis properties, is a classical phenomenal hysteresis model [36]. In addition, the Preisach model [37], neural network model [38], and Bouc–Wen model [39] enjoy similarly great reception. The modifications of these models have drawn extensive attention, involving an online hysteresis identification [35], a suitable model for high frequency [40], a temperature-dependent model [41], and so on. Unfortunately, memorability of PEA and the troublesome calculation of the inverse hysteresis model leads to the modeling error, to some extent, always exists. Therefore, the intractable hysteresis property deserves close attention.

(3) Saturation nonlinearity: In practice, inputs are ultimately constrained [42]. Moreover, a system may be pushed into saturation when facing large unexpected amplitude disturbances [43]. The saturation nonlinearity will seriously influence the performance index of system. Inevitably, the smart structures have to deal with the problem of saturation. For large-scale structures, Ref. [44] presents a fast model predictive control. A block with anti-saturation function is developed Li et al. in [45]. With the help of the sub-structuring technique, Peng et. al propose a distributed control strategy to overcome the issue of input saturation in smart tensegrity structure vibrations [43]. In summary, saturation is a concern in both control and smart structures.

2.2.2. Parametric Uncertainties

Electric and mechanism parameters have been minimized through utilizing of the simplified lumped linear model. However, the acquisition of these parameters is really intractable, not to mention they are not immutable, and the external environment such as temperature [46], boundary conditions, structural variation and so on [47] can cause them to change. Although the modeling processes provide a distinct physical interpretation of the electric and mechanism parameters, they do not bring a practical way of measurement. Especially, as structures become complex, the processes via mathematical formulation become unpractical. System identification technique is another alternative modeling method [48]. For example, the experimental determination of modal parameters is carried out for complex smart structures with multi-actuators and multi-sensors in [49]. The problem with model-dependent controllers is that a good knowledge of the structural dynamics, which means the necessity of accurate parameters, is required.

2.2.3. Control–Structure Interaction

The integration of the actuators, the sensors, and the controllers results in the behavior of smart structures [50]. The controller should take the interactions into account instead of carrying them out separately [51]. The control–structure interactions may lead to performance degradation of the model-dependent controller. It is important to consider the control–structure interaction effect to achieve high performance in structural vibration control [52,53]. The accuracy and efficiency of active vibration control models are highly dependent on the perfection of understanding the interactions between the structure and the controller.

2.2.4. Measurement Error Effects and Measurement Noise

In smart structures, errors in measurements of either position or acceleration inevitably cause poor performance. Piezoelectric sensing technology is widely used [6,54–56]. However, the Piezoelectric effect is the main working principle of piezoelectric sensors. Piezoelectric sensors cannot be used for static measurement because the charge after being acted by external force can be saved only when the circuit has infinite input impedance. This is not the case in practice, so the piezoelectric sensor can only measure dynamic stress. As for the measurement noise, it is a factor that needs to be considered when designing the controller [57–59].

2.2.5. Time Delay

In smart structures, time delays exist widely, such as state delay, input delay, transmission delay or output measurement delay, volume delay, etc. System time delay arising from computational delay and the sampling time of the acquisition card is also a serious challenge in structural vibration systems. The actual collocated placement of accelerometers and piezoelectric actuators is hard to be realized in practical vibration engineering, which is also an important factor for system time delay [60–63]. On one hand, the existence of a time delay makes the controlled variable unable to timely reflect the disturbance to the system, resulting in obvious overshoot and long adjustment time, even causing system instability. On the other hand, the development of time delay feedback control technology provides a new idea for vibration control and uses the time delay to redesign the control system to achieve the optimal control effect [62,64–66]. To sum up, time delay is a significant issue in smart structures.

2.2.6. External Disturbances

Most vibrations are caused by external disturbances. Piezoelectric materials are widely applied in various structures. The following is a brief introduction to the different external disturbances faced by three typical structures. The results are shown in Table 2.

Table 2. External disturbances in several typical piezoelectric structures.

Typical Structures	Common External Disturbances	References
Large space structures	• The spacecraft encounters the impacts of space particles; • Experiences the temperature impacts as it either enters or leaves the Earth's shadow; • Makes a maneuver itself.	[3,30,67–71]
Civil structures	• Non-stationary random excitations such as earthquakes; • Flutter phenomenon; • Fatigue failure.	[72–74]
Rotor system of the helicopters	• Severe environmental conditions such as gusts, blasts, sonic boom, shock waves, fuel explosions, sonic booms, etc.	[75,76]

2.3. Piezoelectric Modal Sensors

One of the primary concerns in the active vibration control (AVC) system is choosing the appropriate sensors. Notice that real-time measuring of the particular structural modal information (such as modal coordinates, modal velocities, etc.), gives significant advantages in the AVC system, regardless of what control approach is used. The use of structural modal information in AVC can improve the stability of the closed-loop system and the problem of control spillover can be reduced. AVC for continuous structures based on modal information can be regarded as controlling multiple single-degree-of-freedom (SDOF) systems in parallel. Over the past thirty years, real-time sensing modal information has been developed as a special area, which is termed modal sensing. Therefore, in this subsection, as an important part of a piezoelectric smart structure, the piezoelectric modal sensors will be briefly reviewed.

In the early years of modal sensing technology, point-type sensors (such as accelerometers) were frequently used to design the modal sensors [77]. The difficulty in modal sensing by using point-type sensors is that a large number of sensors are required to construct a modal filter. The real-time signal processing for the outputs of the point-type sensors can be a significant burden even for very expensive (or high-speed) microprocessors. It means that such a point measurement-based modal sensing system is difficult to implement in real applications. To overcome this difficulty, the design of piezoelectric modal sensors for the AVC system was first proposed by Lee and Moon [78]. The experiment demonstrated that it was possible to design shaped piezoelectric sensors that only measure the particular targeted mode for one-dimensional beam-type structures by using the orthogonal properties of the structural modes. It means that the output signal of the designed sensor is sensitive to targeted structural modal coordinates and other modal coordinates are filtered out by shaping the piezoelectric sensor. Lee et al. [79] further experimentally demonstrated using a piezoelectric modal sensor/actuator for active damping control of the first mode of a cantilever beam. Excellent control performance can be obtained without the spillover phenomenon by using the modal sensor/actuator pair approach.

In general, piezoelectric modal sensors made of polyvinylidene fluoride (PVDF) films are chosen since these add little loading to light structures and in addition, are easy to cut into desired shapes.

Inspired by Refs. [78,79], the different approaches for the design of the shaped piezoelectric modal sensors have been proposed and experimental verified. Mao and S. Pietrzko [80,81] imposed Adomian decomposition method (ADM) to design the shaped piezoelectric modal sensor for uniform and tapered beams under arbitrary boundary conditions. Typically, the length of the piezoelectric modal sensor for beam structure requires covers the whole beam, while the width of the piezoelectric sensor is changed. Friswell [82] presented a new modal sensor in which shapes cover only a part of the beam structure. However, if the modal sensors only cover a small part of the structure, this approach could be quite difficult for practical implementation due to the manufacturing tolerances [82].

The design of piezoelectric modal sensors usually ignores any uncertainty and variability in the host structure, which can have a significant effect on their performance. Adhikari and Friswell [83] presented a robust design approach for piezoelectric modal sensors considering uncertainties and variability in the host beam structure using a discrete approximation. The numerical results show that the modal sensor shapes for the stochastic system can be significantly different from the corresponding deterministic system.

For one-dimensional structures, the shapes of piezoelectric modal sensors can be easily manufactured by varying the sensor width. However, there are still difficulties in implementing shaped modal sensors for two-dimensional structures because the thickness of the sensor should also be varied. To overcome this problem, Sullivan et al. [84] introduced a shaped modal sensor design method for a rectangular simply supported plate by shading the piezoelectric sensors. Donoso et al. [85] further extend this approach to design the shaped modal sensors for shell-type structures. Porn et al. [86] proposed a parametric level set method to design the modal sensor by optimizing the piezoelectric material distribution and polarization profile. Donoso and Guest [87] presented a topology optimization approach to design the shaped modal sensor. Sanada et al. [88] designed an active structural acoustic control (ASAC) system for a rectangular plate by using shaped modal sensors.

As mentioned above, shaped piezoelectric modal sensors allow the selection of particular structural modes with a certain degree of accuracy, while filtering out the remaining part of the structural modal responses. This is achieved by varying the sensitivity of the sensor over its surface. These modal sensors are attractive because these shaped piezoelectric sensors are light and inexpensive. The piezoelectric modal sensors are extended for structural acoustic sensing, for example, Zahui et al. [89] and Rozema et al. [90] used shaped piezoelectric modal sensors to measure the total and local volume displacements of the vibrating beams.

However, there are still difficulties in implementing such sensors due to the complexity of the sensor shapes, especially for two-dimensional plate structures. An alternative approach that can be used to design modal sensors is based on piezoelectric array. An array of piezoelectric patches with corresponding weights is used as a modal sensor, so the weighted combinations of the piezoelectric signals lead to the targeted modal information. Zhong et.al integrated a flexible printed circuit board sensor membrane PVDF arrays for a novel composite beam [91]. Mao et al. [92] measured the amplitudes of radiation modes by using a PVDF array. Trindade et al. [93] presented an experimental application of a piezoelectric array modal sensor for AVC with a rectangular plate. A 30 dB reduction can be achieved around the targeted mode by using a modal sensor. The main advantages of the piezoelectric array modal sensors are that they do not require spatially continuous shaping and do not require a separate layer of the sensor for each targeted mode.

3. Formulation and Applications of ADRC

ADRC was originally proposed by Han under the nonlinear structure, and simplified by Gao in order to design and implement easily for practitioners [19]. The core idea is to take a simple integrator series type as the standard type of the feedback system and regard the part of the system dynamics that is different from the standard type as the total disturbances (including internal disturbances and external disturbances), as shown in Figure 2.

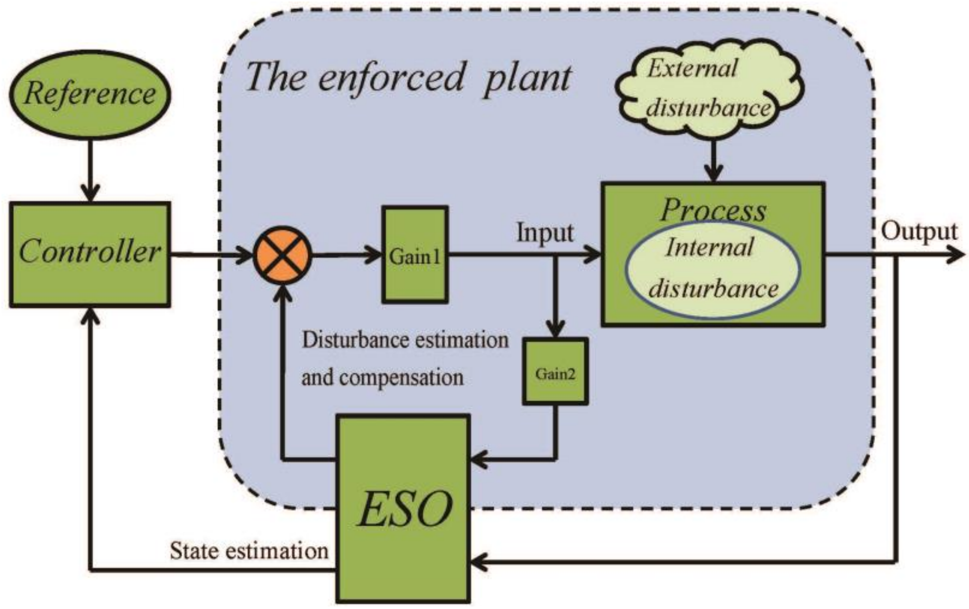

Figure 2. Schematic diagram of ADRC.

According to the idea of ADRC, the flow chart of designing ADRC of smart structure is shown in the Figure 3.

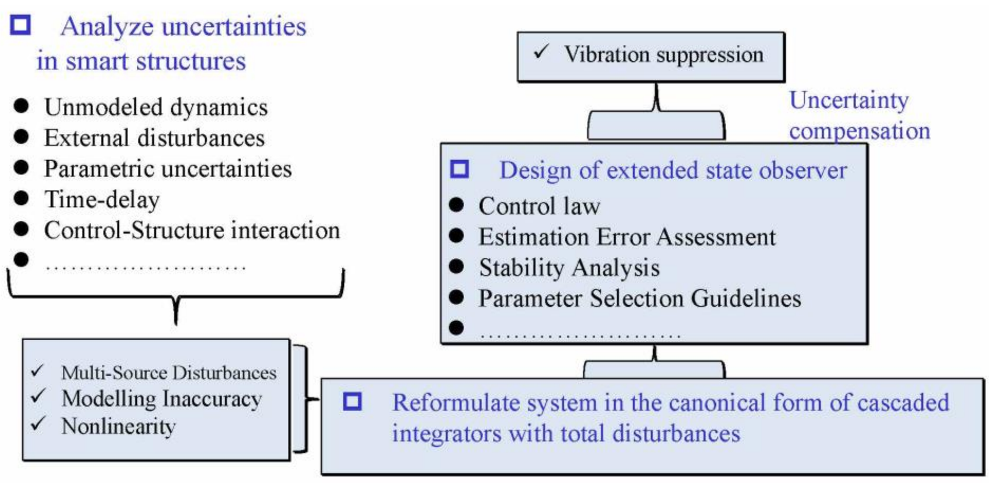

Figure 3. Design flow diagram of ADRC for smart structure.

3.1. System Re-Modeling with Total Disturbances

According to Figures 2 and 3, the first step before using an ADRC is to reformulate a practical control issue in the canonical form of cascaded integrators with generalized disturbances. The model is further simplified by using the concept of total disturbances as follows.

3.1.1. Single Modal

Consider n-th mode of a structure, by simply manipulating the Equation (4), the differential equation form becomes:

$$\ddot{\eta}_n = b_0 u - 2\zeta_n \omega_n \dot{\eta}_n - \omega_n^2 \eta_n + f_n + (b - b_0)u \tag{5}$$

In order to achieve an efficient ESO, the control gain b_0 is introduced. Thus, the total disturbance f is formulated by:

$$f = -2\zeta_n \omega_n \dot{\eta}_n - \omega_n^2 \eta_n + f_n + (b - b_0)u \tag{6}$$

In the process of piezoelectric plate vibration, the changing rate of the structure state has a physical limit. For example, the sudden impact force is related to the change in plate velocity that has their inertia. In brief, in the piezoelectric plate studied, the signals are differentiable with bounded derivatives. In the sequel, the state variables of the piezoelectric plate are defined as $x_1 = \eta_n$, $x_2 = \dot{\eta}_n$. In addition, f is treated as an extended state variable and expressed by $x_3 = f$. Now, the plate model can be constructed as follows:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ b_0 \\ 0 \end{bmatrix} u + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \dot{f} \tag{7}$$

Equation (7) uses the concept of total disturbances to reformulate the model (4) in the canonical form of cascaded integrators to convert model. It is motivated by the fundamental design principle of the ADRC framework, in which the controller is model-independent, and the uncertainties and disturbances are estimated in real time and compensated via ESO.

3.1.2. Multi-Modal

Consider n modes of a structure, they can be generally expressed as:

$$\begin{cases} \ddot{\eta}_1 = -2\zeta_1\omega_1\dot{\eta}_1 - \omega_1^2\eta_1 + b_1u \\ \ddot{\eta}_2 = -2\zeta_2\omega_2\dot{\eta}_2 - \omega_2^2\eta_2 + b_2u \\ \vdots \\ \ddot{\eta}_n = -2\zeta_n\omega_n\dot{\eta}_n - \omega_n^2\eta_n + b_nu \\ y = \eta_1 + \eta_2 + \cdots \eta_n \end{cases} \tag{8}$$

Equation (7) can be rewritten as a single-input single-output system (SISO system) form as:

$$\ddot{y} = -2\zeta_0\omega_0\dot{y} - \omega_0 y + bu + w(\eta, \dot{\eta}) \tag{9}$$

in which $b = \sum_{i=1}^{n} b_i$, ω_0, and ζ_0 are, respectively, the nominal value of natural frequency and damping ratio that can be adjusted, $w(\eta, \dot{\eta}) = -\sum_{1}^{n}[2(\zeta_i\omega_i - \zeta_0\omega_0)\dot{\eta}_i + (\omega_i^2 - \omega_0^2)\eta_i]$ is taken as total disturbances. Thus, the multi-modal structure can be simplified to a SISO system.

It can be seen that the concept of disturbance in the control system has been expanded here, not only the traditional external disturbance, but the uncertainty of the model is also regarded as a disturbance, and this is consciously completed so that the total disturbance can be observed in real time via ESO.

3.2. Design Principles of Convention Linear ADRC for Smart Structure

Based on Equation (7), the LESO of piezoelectric structure can be formulated as follows:

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} + \begin{bmatrix} 0 \\ b_0 \\ 0 \end{bmatrix} u + \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix} [y - z_1] \tag{10}$$

where z_1 and z_2 are the estimations of x_1 and x_2, z_3 is the estimation of f, and β_1, β_2, and β_3 are the tuned positive gains of ESO. The control law is designed as:

$$u = \frac{k_1(r - z_1) - k_2 z_2 - z_3}{b_0} \tag{11}$$

The control diagram of the ADRC-based piezoelectric structure is shown in Figure 4.

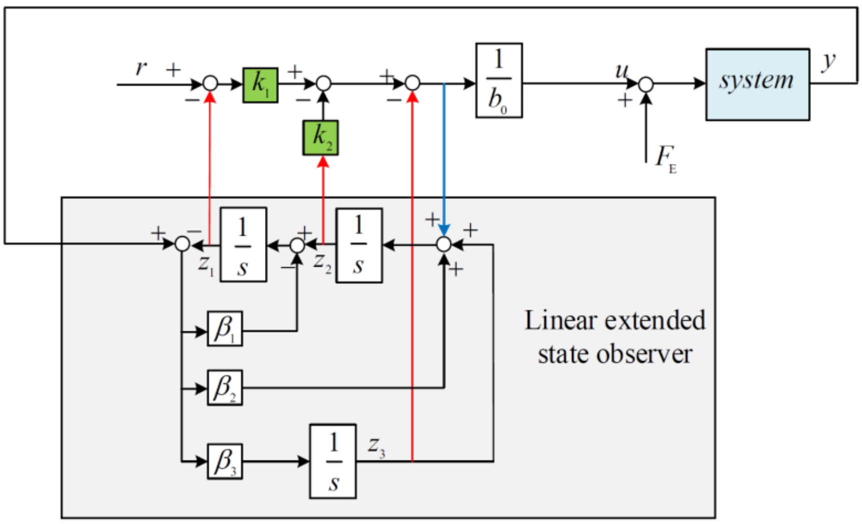

Figure 4. Conventional ADRC control diagram.

4. Theoretical Analysis and Modifications of ADRC

4.1. Theoretical Analysis and Parameter Selection

The analysis of ADRC, including stability, robustness, filtering characteristics, and parameter settings is universal and it is briefly reviewed here.

ADRC's theoretical research has experienced a difficult development process. The reason for this difficulty is due to the grandeur of its ideas: allowing uncertain objects to be nonlinear, time-varying, strong coupling with multiple inputs and multiple outputs, and perturbation. In recent years, the continuous emergence of research results of active disturbance rejection control applications has promoted the gradual development of theoretical research, such as ESO tracking performance to disturbances [94], estimation ability [95]; ADRC for SISO systems [96], MIMO systems [97], non-minimum phase systems [98], systems with mismatch disturbances [99], time delay systems [100,101], systems with modeling uncertainties [102], fractional-order systems [103]; dynamic and performance analysis of ADRC in frequency domain [104], etc. ADRC theoretical analysis is still a challenging problem.

Several factors including estimation precision, system stability, and response dynamics have to be taken into account when selecting proper parameters. The final choice of these parameters may fall into a trial-and-error strategy that could be difficult for practical applications. Research on parameter adjustment has also attracted a lot of attention. The most common and widely used bandwidth method was proposed by Gao [105]. As a well-known design technique, LQR was employed to achieve an optimal tuning of the method based on ESO in [106]. The influence of parameters on the system is studied in Ref. [20] based on the frequency domain method. Ref. [107] proposes a method to optimize parameters to improve system performance. The tuning method based on the intelligent algorithm is also investigated [108]. How to select appropriate parameters for ADRC is still an open problem.

4.2. Modified ADRC for Smart Structure

ADRC has a variety of improvements, and these enhancements bring better performance to it. This subsection will review various improvements and their applications in smart structures.

4.2.1. Modified ADRC for Specific Problems

(1) Time delay: The capability to tackle time delay, the necessity of a stable open loop, and the performance of rejecting uncertainties are the reasons for developing modified ADRC for systems with delays [24]. The main design methods of ADRC for time delay systems [19,24] are: ignoring the time delay method for ADRC [19], increasing order method for ADRC [109], Smith predictor-based ADRC [110], predictive input method for ADRC [101] and delayed input method for ADRC [111,112]. In the application of a smart structure system, Li. et al. proposed a novel vibration control method based on a linear active disturbance rejection controller with a time delay compensation [61]. It introduces a novel differentiator-based smith predictor with the Lissajous curves method into the vibration control loop, which enables an efficient ESO for system delay. An enhanced differentiator-based time delay compensation method is introduced to improve the vibration suppression performance of the NESO-based controller [60]. How to deal with the varying delay and explicitly provide the tuning laws are urgent problems to be solved in the application of ADRC to delayed smart structures.

(2) Hysteresis: As a matter of fact, although the ADRC can achieve acceptable accuracy in tracking periodic low-frequency references, the control performance will be degraded severely in high-frequency tracking tasks owing to a connatural mismatch between the estimation of disturbance and its actual value which limits the compensation of the hysteresis [41]. Combining ADRC with a prior model of hysteresis is the most widely used method, which can reduce the estimation burden of the ESO. An innovative control method that combines active disturbance rejection control and current-cycle iterative learning control

(CILC) is proposed by constructing PEA as a second-order disturbance-based structure to handle both the hysteretic nonlinearities and dynamic uncertainties of PEA [113]. A robust U-model active disturbance rejection control is proposed by incorporating the core idea of the U-model control. A variable bandwidth active disturbance rejection control is proposed and realized on a nanopositioning stage [114]. A phase-leading extended state observer is constructed by adding a phase-leading network to a linear ESO [34]. In [115], the authors presented a novel hierarchical anti-disturbance control solution. The compensation of hysteresis deserves further study.

4.2.2. Modified ADRC by Nonlinear Function

The ADRC can be improved by using nonlinear functions. In fact, the initial ADRC is designed based on the nonlinear function "*fal*", as shown in Equations (12) and (13). The characteristics of the fal function are small errors and small gains with large errors. Zhao and Guo proposed a nonlinear ESO utilizing fractional power functions when compared with the linear ESO, which had good performance in the presence of measurement noise and the advantages of a smaller peaking value [116]. Li et al. applied nonlinear ESO to piezoelectric smart structures and compared it with linear ESO. The comparison results show that nonlinear ESO has a better vibration suppression effect and higher control efficiency [60,117]. The stability of the system is also discussed by using the method of describing the function [60]. The design of an excellent nonlinear function can significantly improve the control performance of ADRC.

$$fal(e,\alpha,\delta) = \begin{cases} \frac{e}{\delta^{1-\alpha}}, & |x| \leq \delta \\ |e|_{\alpha}\text{sign}(e), & |x| \geq \delta \end{cases} \tag{12}$$

$$\begin{cases} e = z_1 - y \\ fe = fal(e, 0.5, \delta), \quad fe_1 = fal(e, 0.25, \delta) \\ \dot{z}_1 = z_2 - \beta_{01} e \\ \dot{z}_2 = z_3 + bu - \beta_{02} fe \\ \dot{z}_3 = -\beta_{03} fe_1 \end{cases} \tag{13}$$

4.2.3. Composite Control Based on ADRC

Combined with ESO, many composite control methods have been proposed, such as model predictive control based on ESO (MPC-ESO) [118], sliding mode control based on ESO (SMC-ESO) [119], adaptive control based on ESO [120] and so on. These methods can generally inherit the advantages of the baseline controller and ESO simultaneously. For example, in order to avoid the sensitivity of sliding mode control to mismatched disturbance, with the help of ESO, Wang et. al lumped the matched disturbance and mismatched disturbance as the total disturbances [121]. The effect of vibration suppression can be improved by combining the common acceleration feedback and ADRC in vibration control [117,122]. An innovative control method combining current-cycle iterative learning control and ADRC was proposed to address the high-precision position tracking problems which are found in PEA systems [41]. Xu et al. developed a two-loop sliding-mode controller to suppress the structural vibration, which improved the chattering of the traditional sliding mode [123]. This kind of composite control is the current research hotspot.

4.2.4. ADRC Based on Other Models

In this section, the ADRC of smart structures based on other models in addition to linear models will be introduced. Although the models obtained by some nonlinear modeling methods often use the simplest control law, the development of ADRC makes it possible to design based on some nonlinear models. First is the fractional order model, which is based on fractional calculus with higher accuracy. ADRC based on the fractional order model is a research hotspot [124–130], and it also has applications in intelligent structures [130]. The other is the infinite-dimensional systems which are described by partial differential equations. ADRC for uncertain partial differential equations has attracted much attention [26,131,132].

Finally, Table 3 summarizes the characteristics of modified ADRC for piezoelectric smart structures.

Table 3. Methods comparison list.

Methods	References	Characteristics
Combined ADRC and Smith predictor.	[60,61]	• Time delay compensation. • The measurement of time delay is completed with the help of Lissajous curves method • Design of smith predictor based on new differentiator.
Phase-leading extended state observer	[34]	• Hysteresis compensation. • Adding a phase-leading network.
Combined ADRC and current-cycle iterative learning control	[41]	• Hysteresis compensation. • The sample-data current-cycle iterative learning control law is simple after using ADRC.
Combined disturbance observer and error-based ADRC	[115]	• Feedback-type disturbance observer. • Error-based ADRC.
Nonlinear ADRC based on "*fa*" function	[117]	• Single-mode vibration control. • Acceleration feedback.
Combined ADRC and nonsingular terminal sliding mode control	[123]	• High accuracy and Finite-time convergence. • Multimodal vibration control.
ADRC based on fractional order controller	[127]	• Improved the performance. • The designed controller meets the separation principle.

5. Overview of Other Anti-Disturbance-Based Vibration Control Methods of Piezoelectric Smart Structures

In addition to ADRC, there are other kinds of vibration technologies based on active disturbance rejection, such as disturbance observer (DO), generalized proportional integral observer (GPIO), equivalent input disturbance (EID), and so on. There are countless links between ADRC and these anti-disturbance control strategies. Jin et al. uses PID to explain ADRC, which shows that ADRC is equivalent to PID plus a second-order low-pass filter [133]. Previous works pointed out connections between ADRC and DO, flat filters, and generalized PI controllers [134–137]. An overview of studies on the equivalence between ADRC and other structures is provided in [134].

These equivalence relations allow a comprehensive articulation of several practical control requirements, such as noise sensitivity and stability margins. As a result, this provides guidance for designing and improving ADRC. From another perspective, the problem may be understood more clearly. Therefore, the application of these methods in intelligent structures will be briefly introduced to deepen the understanding of ADRC.

The design principle of vibration control based on disturbance observer is to estimate the disturbance caused by the structural vibration according to the input and output of the object and the model information of the structure. Its estimated output is used for feed-forward compensation to counteract the adverse vibration of the structure caused by the disturbance, thus improving the vibration suppression ability of the existing feedback control vibration controller [138,139]. The core idea of the GPIO is based on the input/output model of the whole system combined with the time-varying polynomial disturbance model to offset the impact of uncertain disturbance on the system, so as to improve the control performance of the whole system [140,141]. The suppression strategy of EID is based on the degree of influence of disturbance on the system output by setting an input disturbance equal to the external disturbance [142,143].

Due to the existence of a large number of uncertainties, more and more attention has been paid to the research of disturbance rejection control in vibration control. Clarifying the relationship between these methods can achieve twice the result with half the effort. This section reviews the relationship between other methods and ADRC to deeply understand the application of disturbance rejection methods in intelligent structures.

6. Conclusions

This paper reviews the application of ADRC in piezoelectric smart structures, with a detailed review of disturbances in smart structures, including unmodeled dynamics, parameter uncertainties, etc. For intelligent structures, the basic design steps and forms of ADRC were introduced after reformulated system in the form of cascaded integrators. Then, various recently modified ADRCs are classified and reviewed, including analysis and review of improvement ideas and application of existing improvement methods. The relationship between ADRC and other disturbance rejection control methods is reviewed. These reviews are instructive on how to design and analyze ADRC in intelligent structures.

Future research directions include composite control based on ADRC, ADRC with nonlinear functions, fractional ESO, and fractional controllers, all with applications to the various types of piezoelectric smart structures.

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