Chapter

A Review of Modeling and Control of Piezoelectric Stick-Slip Actuators

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Abstract

Piezoelectric stick-slip actuators with high precision, large actuating force, and high displacement resolution are currently widely used in the field of high-precision micro-nano processing and manufacturing. However, the non-negligible, non-linear factors and complexity of their characteristics make its modeling and control quite difficult and affect the positioning accuracy and stability of the system. To obtain higher positioning accuracy and efficiency, modeling and control of piezoelectric stick-slip actuators are meaningful and necessary. Firstly, according to the working principle of stick-slip drive, this paper introduces the sub-models with different characteristics, such as hysteresis, dynamics, and friction, and presents the comprehensive modeling representative piezoelectric stick-slip actuators. Next, the control approaches suggested by different scholars are also summarized. Appropriate control strategies are adopted to reduce its tracking error and position error in response to the influence of various factors. Lastly, future research and application prospects in modeling and control are pointed out.

Keywords: piezoelectric stick-slip actuators, dynamical model, friction model, conventional control, intelligent control

1. Introduction

With the rapid development of nanoscience and technology, precise positioning platforms and related technologies with micron motion range and nanoscale positioning accuracy have been widely applied in various fields, such as micromechanical systems, atomic force microscopy, and biomedical science [1–3]. In nanopositioning technology, system processing and measurement accuracy are increasingly demanding, so the resolution of nanopositioning needs to be achieved for the positioning system. Piezoelectric actuators are widely used in devices to achieve precise positioning because of their small sizes, simple structure, and high resolution. However, it cannot achieve long-distance motion owing to its limited motion range. Therefore, infinite stroke motion can be achieved by combining the piezoelectric actuator principle and the frictional inertia principle. The piezoelectric stick-slip actuator with high resolution and long stroke has advantages that other types of actuators do not have. The introduction and review of other types of actuators can be discovered in the literature [4]. The development and research of piezoelectric rod-slip actuators have been a very active field for several decades. A large number of studies on precision positioning stages based on rod-slip actuators have been carried out at home and abroad.

In the process of the stick-slip actuator, it is often affected by a variety of factors, such as the electrical and hysteresis characteristics of the piezoelectric element, dynamic characteristics of the piezoelectric stack, the mechanical structure, and friction characteristics between slider and drive rod. By analyzing the motion law of the main influencing factors, some non-significant nonlinear factors can be appropriately simplified in the process of establishing the model. Peng et al. proposed an end-effector model considering the linear dynamics and hysteresis characteristics of the piezoelectric stick-slip actuator, as well as the friction of the end-effector. However, the model is suitable for piezoelectric stick-slip actuators with horizontal movement of the end-effector. The effect of gravity should be taken into account in subsequent model studies [5]. The structure of the piezoelectric stick-slip actuator is simple, but since the system relies on the frictional drive for long-distance positioning, there are uncertainties and disturbances. To achieve great motion characteristics, the control requirements of the system are extremely important. The control method is mainly divided into open-loop control and closed-loop control. The open-loop control is often used to compensate for the influence of hysteresis characteristics, and the adjustment and control method is used to realize positioning and tracking. Song et al. proposed feedforward control based on the Preisach model to eliminate the hysteresis characteristics [6]. Li et al. proposed a parasitic-type piezoelectric actuator, and this control strategy was used in scanning mode (high precision motion) to improve the positioning accuracy simply and effectively [7].

In the past few decades, a lot of research has been conducted on the modeling and control of hysteresis nonlinearity of piezoelectric actuators. In this paper, we plan to focus on the piezoelectric stick-slip actuator. Section 2 introduces various models and modeling methods under different characteristics of piezoelectric stick-slip actuators and summarizes the overall comprehensive model including each sub-model. Section 3 reviews various control schemes of the piezoelectric stick-slip actuator, including open-loop control and closed-loop control, and presents its limitations and related challenges. Finally, summarizes the problems in modeling and control of the piezoelectric stick-slip actuator and the future development direction in Section 4.

2. Modelling of piezoelectric stick-slip actuators

The piezoelectric stick-slip actuator is a type of actuator that uses the inverse piezoelectric effect and the friction principle to realize the stepping displacement. Its motion process is more complex and influenced by more factors. Therefore, the establishment of a piezoelectric stick-slip actuator model needs to reflect as many motion laws as possible. By analyzing the principle of stick-slip drive and establishing a comprehensive representative model of piezoelectric stick-slip drive based on a simplified model. On the one hand, the influence of each factor on the system can be analyzed by simulation. On the other hand, for the control method containing the system model, the establishment of the model is the theoretical basis for control, and the accuracy of its model directly affects the performance of the control system.

A typical piezoelectric stack-frictional rod type consists of four principal parts—the fixed part, the piezoelectric stack, the frictional rod, and the slider. The piezoelectric element elongates and contracts under the action of a sawtooth wave drive signal driving the friction rod into a corresponding reciprocating motion. The slider is displaced forward by the frictional force with the friction rod and its own inertia. The basic drive principle of a piezoelectric stick-slip actuator is illustrated in **Figure 1**. The drive process is divided into a stick phase and a slip phase within one cycle, and its force analysis is shown in **Figure 1b**. In the sticky stage, when a slowly increasing voltage is added to the piezoelectric element, the piezoelectric element slowly extends to drive the friction rod to the right. At this time, the friction force between the slider and the friction rod is greater than the inertia force. The slider and the friction rod remain relatively stationary and move together with the right S_0. At the slip stage, the voltage loaded on the piezoelectric element disappears quickly, and the piezoelectric element contracts quickly to the initial position. At this time, the inertia force between the slider and the friction rod is more important than the friction force and drives the slider to produce a backward displacement S_1 to the left. The effective step in each cycle is ΔS. The drive can achieve continuous motion to the right by continuously repeating the motion process.

Research shows that the modeling accuracy of piezoelectric stick-slip actuators is mainly determined by the following aspects—the hysteresis effect of the piezoelectric stack, the relationship between the driving voltage and the driving force, the model of the mechanical structure of the piezoelectric stick-slip actuator, and the friction model between the slider and the friction rod. Therefore, a representative integrated model of piezoelectric stick-slip actuators is discussed based on these factors in this paper.

2.1 Electromechanical coupling model for piezoelectric stick-slip actuators

The piezoelectric actuator part is an electromechanical coupling system. When a certain drive voltage is applied, the piezoelectric actuator generates a certain displacement and output force because of the inverse piezoelectric effect. The modeling of the piezoelectric actuator needs to reflect the relationship between the driving

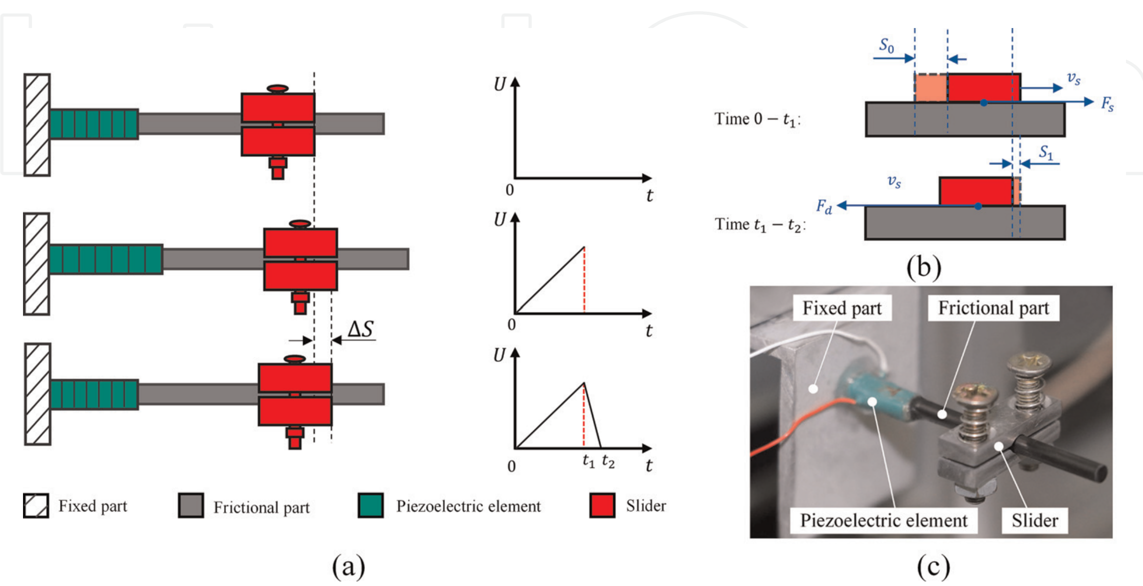

Figure 1.
Operation principle. (a) Driving principle of the stick-slip actuator. (b) Force analysis of the stick-slip actuator. (c) The actual object of the stick-slip actuator.

voltage and the deformation and output force generated by the piezoelectric actuator at the same time, which are coupled with each other.

To quantitatively analyze a system, it is necessary to describe the dynamics of the system through a mathematical model. This enables more information about the system to be described, resulting in better system control. Adriaens et al. pointed out that if the piezoelectric positioning system is properly designed, a second-order approximate modeling approach can be used to represent the dynamics of the system very well [8]. Typically, it can be viewed as a simplified spring-damped mass second-order system with a friction bar. Its linear dynamics is represented as

$$m\ddot{x} + c\dot{x} + kx = F_p - F_f \tag{1}$$

where x is the displacement of the slider, c and k denote the damping and stiffness of the piezoelectric drive stack, and m denotes the total mass of the piezoelectric stick-slip actuator. F_p is the output force of the piezoelectric stack, and F_f is the frictional reaction force between the slider and the friction rod.

There are both hysteresis and creep effects in the process of applying a voltage to the ends of the piezoelectric stack. When the nonlinear characteristics of the system are not considered, the piezoelectric actuator input voltage and output force can be expressed as

$$F_p = K_h u(t) \tag{2}$$

where K_h is the conversion ratio of input voltage to output force and $u(t)$ is the drive voltage of the upper piezoelectric driver.

2.2 Hysteresis model for piezoelectric stick-slip actuators

In the ideal case, the output displacement of the piezoelectric stick-slip actuators is linearly related to the input control voltage curve. Due to the inherent characteristics of this material, there are certain nonlinear characteristics such as the hysteresis effect and creep phenomenon in the actual driving process. However, because the creep effect is so small that it is mostly ignored and the hysteresis effect is mainly considered in the existing literature. The hysteresis phenomenon refers to the non-coincidence between the boost displacement curve and the bulk displacement curve when the drive voltage is applied to the piezoelectric driver. The hysteresis model is used to represent the force generated by the piezoelectric driver with a new equation as

$$m\ddot{x} + c\dot{x} + kx = H(t) - F_f \tag{3}$$

Currently, they can be broadly classified into physical and phenomenological models based on the modeling principles. Physical models are based on the physical properties of materials, among which the Jiles-Atherton model and Ikuta-K model are more common [9, 10]. However, physical modeling is based on the physical properties of the material, so the model implementation is difficult and affects the generality of the physical hysteresis model. Phenomenological models are based on input-output relations of hysteresis systems and are described using similar mathematical models. There are three broad categories based on the modeling approach, operator hysteresis models, differential equation hysteresis models, and intelligent hysteresis models.

2.2.1 Operator hysteresis model

The common operator hysteresis models are the Preisach model, Prandtl-Ishlinskii (PI) model, and Krasnosel'skii-Pokrovskii (KP) model.

The Preisach model was first used to describe the hysteresis phenomenon in ferromagnetic materials. It was then gradually extended to describe the hysteresis behavior of smart materials, such as piezoelectric ceramics and magnetically controlled shape memory alloys. It is one of the most frequently studied nonlinear models of hysteresis [11]. The model consists of an integral accumulation of relay operators in the Preisach plane. The relay operator is shown in **Figure 2a**. Its mathematical expression is given by

$$y(t) = \iint\limits_{P} \mu(\alpha, \beta)\gamma_{\alpha\beta}[u(t)]d\alpha d\beta \tag{4}$$

where $u(t)$ and $y(t)$ represent the input and output of the Preisach model, $\mu(\alpha, \beta)$ is the weight function of the relay operator corresponding to the Preisach plane, $\gamma_{\alpha\beta}$ represents the output of the relay operator, α and β are the switching thresholds of the relay operator.

Based on the previous work, Li et al. proposed that a multilayer neural network can be used to approximate the Preisach model. It can use any algorithm trained for neural networks to identify the model. The model is more flexible to adapt to different working conditions than the conventional model [12]. Later, Li et al. proposed a transformation operator for neural networks that can transform the multi-valued mapping of Lagrange into a one-to-one mapping. By adjusting its weights, the neural network model is made applicable to different operating conditions. The drawback that the Preisach model cannot be updated online is solved [13].

Both the PI model and the KP model evolved from the Preisach model. The PI model has a single threshold and two continuum hysteresis operators, the reciprocal inverse play operator and the stop operator [14], as shown in **Figure 2b** and **2c**. Therefore, the PI model can be derived from the PI inverse model by the stop operator, which can be easily used to design feedforward control compensators by the inverse model. The KP model uses a modified and improved Play operator with its corresponding density function superimposed for hysteresis modeling. While the traditional play operator has only one threshold that determines its width and

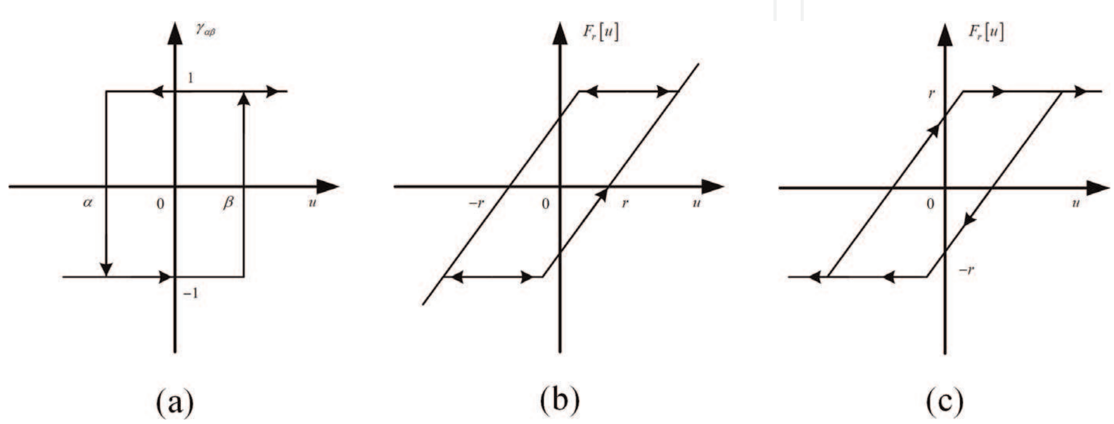

Figure 2.
Operators. (a) Relay operator. (b) Play operator. (c) Stop operator.

symmetry, the KP operator has two different thresholds, enabling it to describe more complex hysteresis nonlinear behavior [15].

2.2.2 Differential equation hysteresis model

The common differential equation hysteresis models include the Duhem hysteresis model, the Bouc-Wen hysteresis model, and the Backlash-like hysteresis model. P. Duhem et al. proposed the Duhem model, which is a differential equation. The model was later improved by Coleman and Hodgdon and applied to describe the hysteresis behavior of piezoelectric ceramics [16]. Its common mathematical expression is given by

$$\dot{x} = \alpha_D|\dot{u}|[f(u) - x] + g(u)\dot{u} \tag{5}$$

where x and u represent the output displacement and input voltage of the Duhem model, and α_D represents the model parameters of the Duhem model, which is a positive constant. The functions $f(u)$ and $g(u)$ determine the shape and performance of the input-output hysteresis curve of the Duhem model.

Although the Duhem model is also applied to describe the piezoelectric ceramic hysteresis problem, its application in engineering is greatly limited due to the difficulty of solving the model inverse model. Su et al. proposed a simplified dynamic hysteresis Backlash-like model based on the Duhem model [17]. This model has fewer parameters compared to the Duhem model and is a first-order differential equation with the mathematical expression

$$\dot{x} = \alpha_B|\dot{u}|[cu - x] + \beta_B\dot{u} \tag{6}$$

where x and u represent the output displacement and input voltage of the Backlash-like model, α_B, c and β_B are constants.

The Bouc-Wen model was originally proposed as a differential equation by Bouc [18] and was later refined by Wen [19] to form the current Bouc-Wen model. The classical Bouc-Wen model can describe a large class of hysteresis phenomena and has a concise expression [20], which is given as follows

$$\begin{cases} y(t) = kv(t) - h(t) \\ \dot{h}(t) = \alpha\dot{v}(t) - \beta|\dot{v}(t)||h(t)|^{n-1}h(t) - \gamma\dot{v}(t)|h(t)|^n \end{cases} \tag{7}$$

where k denotes the scale factor of the system input to the output of the hysteresis part, α, β, γ , and n denote the parameters of the hysteresis part of the model. The Bouc-Wen output $y(t)$ consists of a proportional linear part $kv(t)$ and a hysteresis nonlinear part $h(t)$.

The Bouc-Wen model is simple in form and has few identification parameters, which is convenient for controller design. However, it cannot completely describe the hysteresis characteristics of piezoelectric ceramics, its accuracy is low and it is only applicable to single frequency signals. The Bouc-Wen model is difficult to accurately describe the hysteresis phenomenon under the effect of frequency signals [21]. Therefore, the application of this model in practical engineering is greatly limited.

2.2.3 Intelligent hysteresis model

In addition to the above hysteresis models, there are some other classes of hysteresis models used in hysteresis modeling of smart materials, such as neural network models polynomial models, and other nonlinear models. Gan et al. proposed a polynomial model for the hysteretic nonlinearity of piezoelectric actuators. Experimental results show that the proposed model has higher modeling accuracy than the conventional PI model [22]. Cheng et al. proposed a method for nonlinear model prediction. First, a multilayer neuron network is used to identify the nonlinear autoregressive sliding average model of piezoelectric ceramics. Then, the tracking control problem is transformed into an optimization problem for model prediction. Finally, the Levenberg-Marquardt method is used to solve the numerical solution of the nonlinear minimization [23].

There are some other models, for example, Zhang et al. proposed a proposed Rayleigh model to describe the hysteresis characteristics of the piezoelectric drive system. The parameters of the rate-dependent Rayleigh model were obtained and validated based on the functional and experimental data [24]. Li et al. proposed a simplified interval type 2 (IT2) fuzzy system for hysteresis modeling of piezoelectric drives. In the experiments, gradient resolution and inverse resolution are used to identify the IT2 fuzzy hysteresis model [25]. Although these models are not as widely applied as the three major classes of models, they can often achieve good results in some cases when dealing with the hysteresis characteristics in some specific situations.

2.3 Selection of friction model

The output of the drive system is ultimately transferred to the slider in the form of friction, so the choice of friction model will directly affect the accuracy of the stick-slip drive platform model. At present, with the in-depth research of many international scholars on friction models, a variety of friction models have been established, which can be broadly divided into two categories, static friction models and dynamic friction models. Static friction models describe the friction force as a function of relative velocity. The dynamic friction model describes the friction force as a function of relative velocity and displacement. In contrast to static friction, which only considers the case where the relative velocity is not zero, the dynamic friction model uses differential equations to refer to the case where the relative velocity speed is zero. Therefore, in terms of accuracy, the dynamic friction model is more comprehensive and realistic than the static model. However, in addition to the accuracy of the friction model, it is also necessary to consider the complexity of the model, not all cases need to use the dynamic friction model.

2.3.1 Static friction model

The most widely used models in static friction modeling can be broadly classified into a series of coulomb and the stribeck model. Leonardo da Vinci took the lead in discovering that friction is related to the mass of an object and constructed a model. The model considers that the frictional force is proportional to the mass of the object and opposite to the direction of motion. Later this model was improved and called the coulomb model with the expression for friction

$$F_f = F_c \operatorname{sgn}(v) \tag{8}$$

where F_f is the friction force, F_c is the Coulomb friction force, and $\operatorname{sgn}(v)$ is the sign function.

In some studies, classical friction models have been used to represent the friction between the slider and the friction bar. The four static friction models commonly used in the early days are shown in **Figure 3** [26]. However, the slider step is only a few tens of nanometers to a few microns. The friction at this point is determined by the pre-slip displacement, which is the motion of the object before it is about to slide formally. When the friction surface is rough, the Coulomb friction model cannot accurately predict the friction force at pre-slip. Experiments have shown that in the pre-slip domain, the friction force depends on the micro-displacement between the two contacting surfaces [27]. However, the Coulomb friction model does not accurately predict this effect and will result in a relatively large error in the system. Therefore, a more accurate friction model is needed to describe the friction between the drive block and the terminal output.

These models need to exhibit some important static and dynamic properties of friction, such as the stribeck effect, Coulomb friction, stick friction, and pre-slip displacement. Li et al. proposed the stribeck model, which was the first model to describe dynamic and static frictional transition processes [28]. Its mathematical expression is as follows

$$F_f = \left(F_c + (F_s - F_c)e^{-|v/v_s|\varsigma_s}\right)\operatorname{sgn}(v) + bv \tag{9}$$

where F_s is the maximum static friction, F_c is the Coulomb friction force, b is the coefficient of stick friction, v_s is the stribeck effect velocity value, and ς_s is the empirical constant.

It not only reflects the linear relationship between dynamic friction and velocity but also expresses the change of friction during the transition between dynamic and static friction. It lays the groundwork for future research and the establishment of a dynamic friction model.

2.3.2 Dynamic friction models

Dahl et al. proposed the Dahl model, which is a dynamic friction model [29]. It describes for the first time the pre-slip displacement in a friction model, represented by the partial differential equation

$$\frac{dF_f}{dx} = \sigma\left(1 - \frac{F_f}{F_c}\operatorname{sgn}(v)\right)^{\alpha} \tag{10}$$

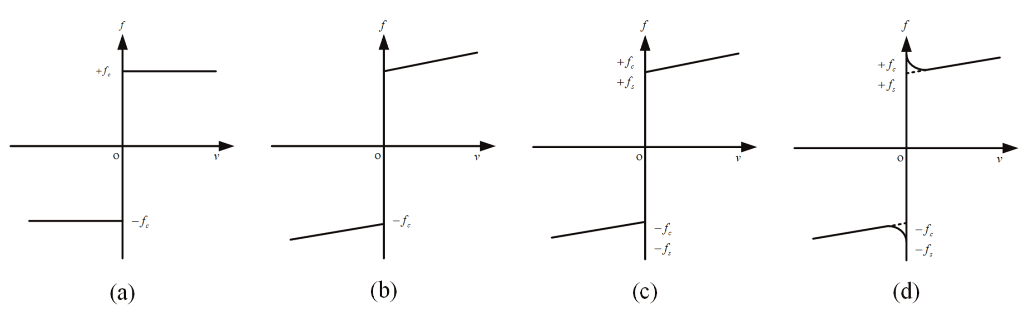

Figure 3.
Four classical static friction models. (a) Classical Coulomb friction model. (b) Coulomb and stick friction models. (c) Static friction, coulomb, and stick friction models. (d) Stribeck model.

where x is the shape variable and σ is the stiffness coefficient. α determines the shape of the curve.

However, the model does not capture the variation of the static friction phase and also does not explain the stribeck phenomenon. It is far from an adequate description of the stick-slip-driven friction interface. However, due to its simple and accurate expressiveness, it provides a solid foundation for the subsequent dynamic modeling.

Based on the study of the Dahl model, the French scholar Canudas proposed the LuGre model [30]. Its principle formula is

$$\begin{cases} F_f = \sigma_0 z + \sigma_1 \dfrac{dz}{dt} + \sigma_2 v \\ \dfrac{dz}{dt} = v - \dfrac{z}{g(v)} |v| \\ g(v) = \dfrac{1}{\sigma_0} \left[F_c + (F_s - F_c) e^{-(v/v_s)^2} \right] \end{cases} \tag{11}$$

where α_0 denotes the stiffness coefficient of the elastic bristle, α_1 denotes the system damping coefficient, α_2 is the coefficient of stick friction, v is the relative velocity of the object surface, z is the mean deformation of the friction surface, and $g(v)$ is the described stribeck effect.

The LuGre model introduced the stribeck effect in addition to combining the idea of pre-slip displacement in the Dahl model. The idea of the bristle effect was designed to address the changing situation of the static friction phase. Swevers et al. proposed a new structure of the dynamic friction model [31]. The non-local memory hysteresis function and the modeling of arbitrary transition curves were added on the basis of the LuGre model. This allows the model to accurately describe the experimentally obtained friction characteristics, stribeck friction during slip, hysteresis behavior during slip, and stick-slip behavior. Since the structure of the obtained model is flexible, it can be further extended and generalized.

2.4 Comprehensive model of piezoelectric stick-slip actuators

By combining the above models and considering other influencing factors, a comprehensive dynamics model considering the electrical model of the piezoelectric stick-slip actuator, the hysteresis effect, the linear dynamics performance, and the frictional characteristics of the system can be obtained, as shown in **Figure 4**.

In the stick-slip drive system, the output force of the piezoelectric stack is first obtained by the change of voltage at both ends of the piezoelectric element. Then, the electromechanical conversion model of the drive transmission system composed of the piezoelectric stack and the flexible transmission mechanism is transformed into the displacement and force output of the transmission system. Finally, the displacement is transferred to the slider by the kinematic friction conversion, and the final

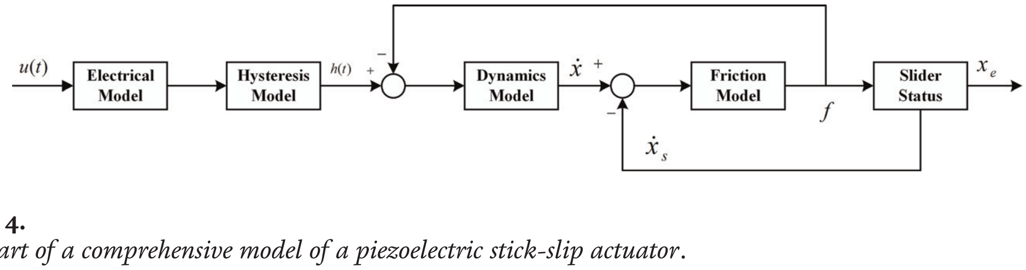

Figure 4.
Flowchart of a comprehensive model of a piezoelectric stick-slip actuator.

displacement output is obtained. The mathematical equation of its integrated model is as follows

$$\begin{cases} m\ddot{x} + c\dot{x} + kx = H(t) - F_f \\ m_s\ddot{x}_s = F_f \\ x_e = x - x_s \end{cases} \tag{12}$$

where $H(t)$ can be given by the previous hysteresis model [i.e., (4)–(7)]; F_f can be given by the friction model [i.e., (8)–(11)]; x_s is the backward displacement of the slider under the action of dynamic friction; and x_e is the forward displacement of the slider.

Wang et al. developed a kinetic friction model of the actuator and investigated the effect of the input drive voltage on the viscous slip motion of the actuator through simulation [32]. Nguyen et al. used the method of dimensionality reduction to describe the frictional contact behavior of the stick-slip microactuator. The model accurately predicts the frictional contact behavior of the actuator on different geometric scales without using any empirical parameters [33]. Piezoelectric stick-slip actuators also have more complex dynamic characteristics. The ability to simulate a wide range of dynamic characteristics is the direction of increasing research. Shao et al. found that the contact behavior of the piezoelectric feed element produced an inconsistent displacement response. So the Hunt-Crossley kinetic model, LuGre model, distributed parameter method combined with Bouc-Wen hysteresis model were used to model the viscous slip actuator. This model can effectively model the step inconsistency in the front-to-back direction of the actuator [34]. Wang et al. proposed a stick-slip piezoelectric actuator dynamics model considering the overall system deformation. The model introduced stiffness coefficients and damping coefficients for the whole system and successfully simulated three single-step characteristics, namely, backward motion, smooth motion, and a sudden jump for the first time [35]. Due to a large number of parameters in the dynamic model, the accurate identification of each parameter will be quite difficult. Therefore, more accurate identification of simulation parameters needs further research, which may be our future work.

3. Control schemes of piezoelectric stick-slip actuators

The piezoelectric stick-slip actuator introduces mechanical structures, such as friction rods and linear cross roller guides on the basis of piezoelectric stacks. A sawtooth wave signal is applied to the piezoelectric stack to achieve a stepping large stroke and high precision motion. In the actual application process, the traditional mechanical structure can no longer meet the demand of real positioning accuracy due to the complex nonlinear effects in the system and the influence of external disturbances. Therefore, intelligent control algorithms combined with computer hardware devices are usually introduced to eliminate or reduce the impact of the above problems on motion accuracy. This section mainly discusses the existing controller design methods from two parts—open-loop control and closed-loop control.

In this paper, control schemes and hardware facilities for piezoelectric stick-slip actuators are briefly described in most of the literature. Depending on whether a closed-loop is formed, the main categories are feedforward control, feedback control,

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and composite control with a combination of feedforward and feedback. The inverse model-based control is mostly feedforward control, which is usually used to compensate for the hysteresis characteristics of piezoelectric stick-slip actuators. The control system is shown in **Figure 5**, y_d is the expected input, v_{inv} is the theoretical input under the expected output value, y is the actual output value.

Feedback control is the real-time feedback of the actual measured displacement through data measurement equipment, such as sensors, and the feedback value is one of the inputs of the controller. Feedback control can effectively improve the robustness of the control system, and its control mode is shown in **Figure 6**. Where, v is the output of the feedback controller.

In actual control, simple feedforward control and feedback control cannot meet the control demand. Therefore, in most cases, researchers combined the advantages of feedforward control and feedback control, usually the feedforward control and feedback control of the compound control scheme are applied to the piezoelectric stick-slip actuator position tracking control. The control system is shown in **Figure 7**.

3.1 Conventional open-loop control of piezoelectric stick-slip actuators

Feedforward control is essentially an open-loop control. However, in the overall control of piezoelectric stick-slip actuators, the advantages of this control method are very limited. This has been found by many scholars—since the voltage changes for each step displacement are very fast, there is almost no hysteresis, creep effect, and the use of feed-forward control in this motion mode is not necessary.

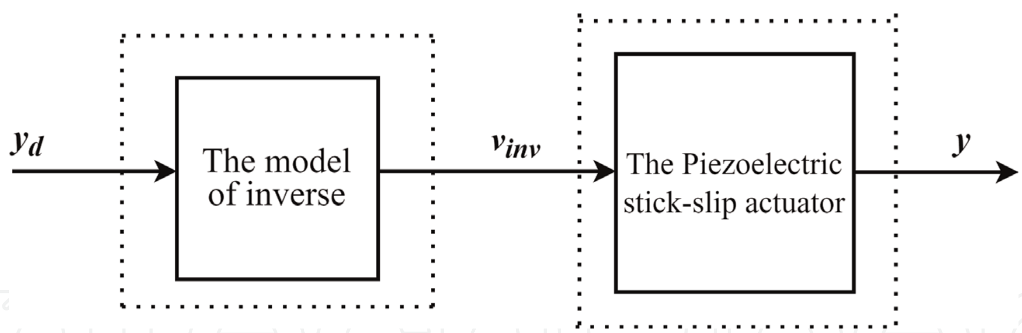

Figure 5.
Feedforward control system principle based on inverse model.

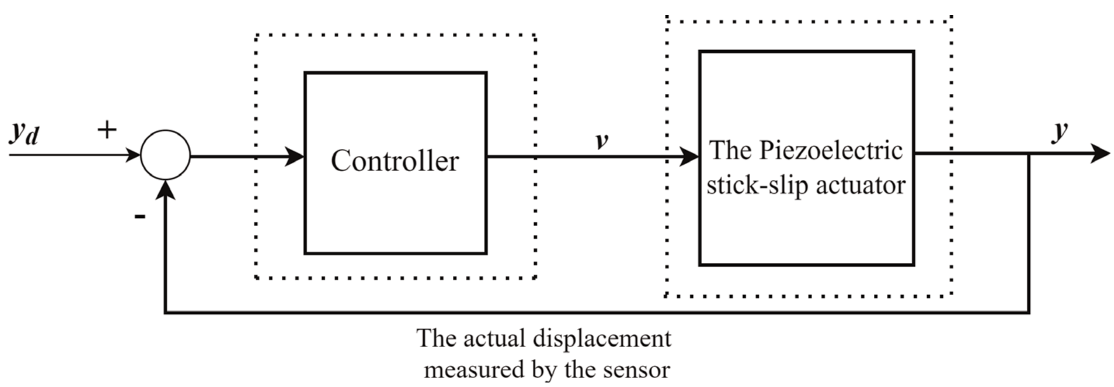

Figure 6.
Feedback control system principle.

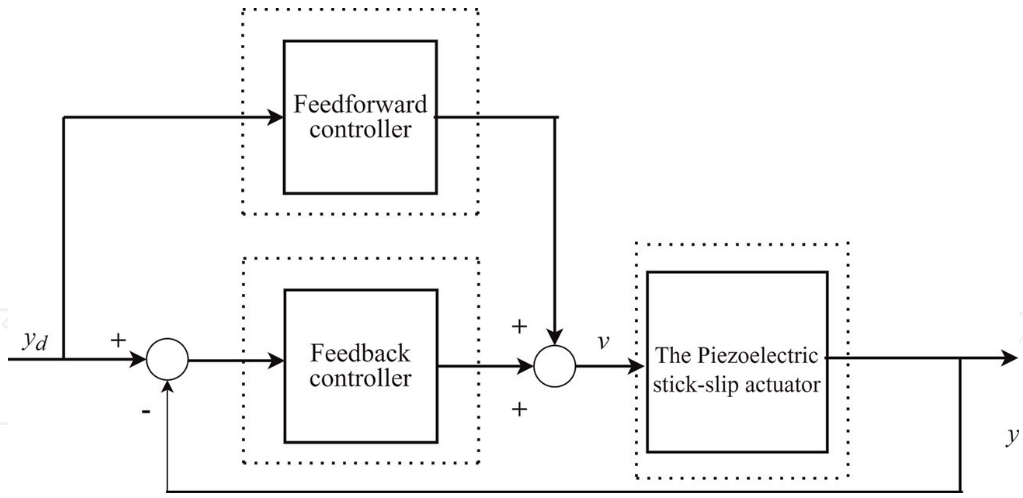

Figure 7.
Feedforward and feedback compound control system.

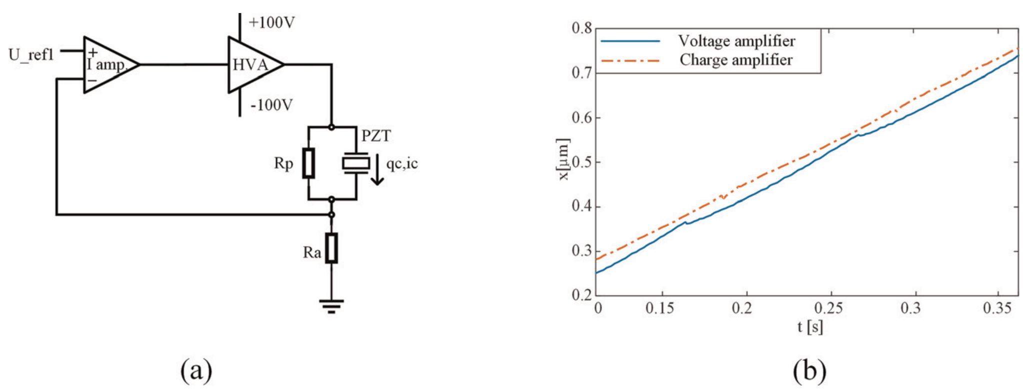

Figure 8.
(a) A simplified circuit diagram. (b) Experiment effect.

Feedforward control is often used to improve the quality of the end motion output of piezoelectric stick-slip actuators. Holub et al. compensated for the hysteresis of piezoelectricity by varying the amplitude of the input voltage for position errors and hysteresis modeling [36]. Chang et al. compensate for hysteresis by changing the phase lag of the actuator [37].

Feedforward control of end-effectors is challenging as the control accuracy of feedforward control is heavily dependent on the accuracy of the above model. The main source of difficulty comes from the many problems in the real system, including the hysteresis of the piezoelectric, the creeping nature, and the non-linearity of the frictional motion, the vibration between the stick and sliding points, the wear of the material between the movers and the stator, and other uncertainties [38].

Another feed-forward control by some scholars-charge control to compensate for hysteresis in the actuator. Špiller et al. developed a hybrid charge-controlled driver that slides by generating a high-voltage asymmetric sawtooth wave and feeding it into a capacitive load to compensate for the piezoelectric hysteresis as well as to achieve fast back-off. A simplified circuit diagram of the piezoelectric driver is shown in **Figure 8a**. This control method combines a charge control scheme with a switch is an effective solution, and the proposed hybrid amplifier has better motion linearity as shown in **Figure 8b** [39].

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The control of piezoelectric stick-slip actuators is usually divided into one-step control stage and sub-step control stage, also known as step mode and scan mode. Step mode refers to the piezoelectric stick-slip actuator moving forward at a fixed step size and a fixed frequency when it is far from the desired position. Until the error between the actual position and the desired position is less than the single-step displacement of the piezoelectric stick-slip actuator, the precise positioning is realized by controlling the elongation of the piezoelectric stack, which is called the scanning control stage. In the stepping mode, the voltage changes rapidly and there is almost no creep. At the same time, in the stepping mode, the control accuracy is not necessary. Therefore, in the control process of stick-slip motion, there are few overall feedforward control cases. And feedforward control is usually implemented in the scanning control stage. The core component of the piezoelectric stick-slip actuator is the piezoelectric stack, which moves through the inverse piezoelectric effect of the piezoelectric stack. Compared with the motion control of the piezoelectric stick-slip actuator, feedforward motion control of the piezoelectric stack actuator is more mature. Chen of Harbin Institute of Technology defined a new function named mirror function, which connected the dynamic hysteresis model with the classical Preisach model and established a new dynamic hysteresis model to describe the input-output relationship of the piezoelectric actuator under different conditions. On this basis, a feedforward control scheme based on the dynamic hysteresis inverse model is designed [40].

In addition, Ha et al. experimentally identified the hysteretic parameters of the Bouc-Wen model, and on this basis designed a feedforward compensator to compensate for the influence caused by the nonlinearity of the hysteretic effect. Finally, the simulation results of the compensator and the designed voltage waveform are given to realize the feedforward control of the piezoelectric stack [41]. Wei et al. proposed a feedforward controller based on an improved rate-dependent PI hysteresis inverse model, which achieved the expected effect [42]. In recent years, Zhang et al. also proposed a third-order rate-dependent Rayleigh model to describe the hysteresis nonlinearity of piezoelectric stacks. And proposed a feedforward control scheme based on the inverse third-order rate-dependent Rayleigh model, which also verified the effectiveness of the method through experiments [43]. Feedforward control often plays an obvious role in hysteresis compensation. In the future piezoelectric stick-slip drive controller design, the existing piezoelectric stack feedforward control methods can be used for reference to realize the feedforward control in the scanning stage. Simple feedforward control has poor robustness in the application, so most researchers use compound control to improve the control accuracy.

3.2 Conventional closed-loop control of piezoelectric stick-slip actuators

Piezoelectric stick-slip actuators are affected in practice by factors such as environmental vibration and their own nonlinear characteristics, and their controllability becomes poor. Therefore, appropriate control methods are needed for closed-loop control to meet the actual working requirements. Zhong B et al. found that differences in object surface roughness and wear can cause inconsistent velocities during the movement of a piezoelectric stick-slip actuator. Therefore, a dual closed-loop controller for velocity and position was designed to achieve high accuracy positioning. Its principle of double closed-loop control is shown in **Figure 9**. The experimental results show that the standard deviation of the speed of the controller is less than 0.1 mm/s, and the repeated positioning accuracy reaches 80 nm, both of which achieve a good control effect [44]. The design of the controller considers a more accurate speed

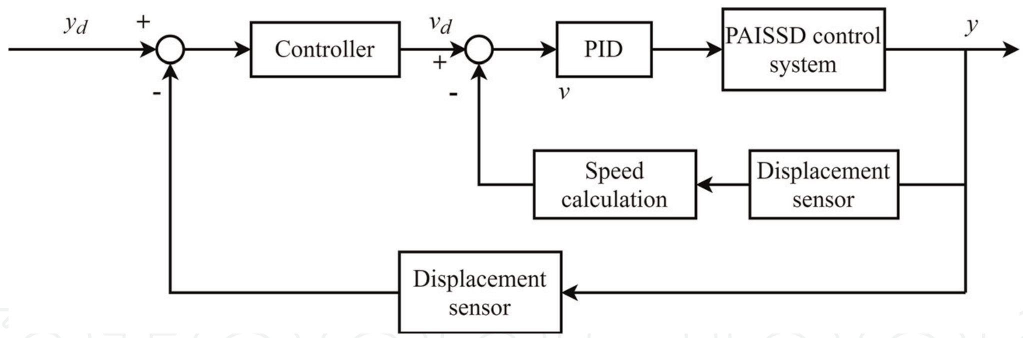

Figure 9.
Double closed-loop control principle.

control scheme, which has a high reference value for realizing the fast positioning of piezoelectric stick-slip actuators. Rong et al. introduced strain gauge as positioning sensor of the precision manipulator with piezoelectric stick-slip actuators and developed a displacement prediction method based on this. The feedforward PID control method is used throughout the system to improve the dynamic performance of the system. As shown in **Figure 10a**, it is the simulation of displacement-prediction control positioning performance (target displacement of 5.5 μm). **Figure 10b** shows the comparison of displacement response under the open-loop control and displacement response under the displacement-prediction control (target displacement of 20 μm). It can be seen from the experimental results that the 200 nm steady-state error of the proposed control method is much lower than that of the open-loop control [45]. The commonly used classical control methods are difficult to achieve high control accuracy in practical applications due to the limitations of parameters, weak automatic regulation and poor robustness.

Rakotondrabe et al. designed a micro-positioning device based on a stick-slip actuator. The control process is divided into a step mode and a scan mode, where the scan mode is precisely controlled by a PI controller [46]. Theik et al. used an inertial piezoelectric actuator to suppress the vibration of the hanging handle and designed three controllers—PID manual setting, PID self-setting, and PID-AFC. The best damping effect was achieved by experimentally comparing the PID-AFC controller. When the mass of the inertia block is larger, the vibration damping effect is more obvious [47]. These control methods are developed by the classical control theory in the actual control process of piezoelectric stick-slip actuators.

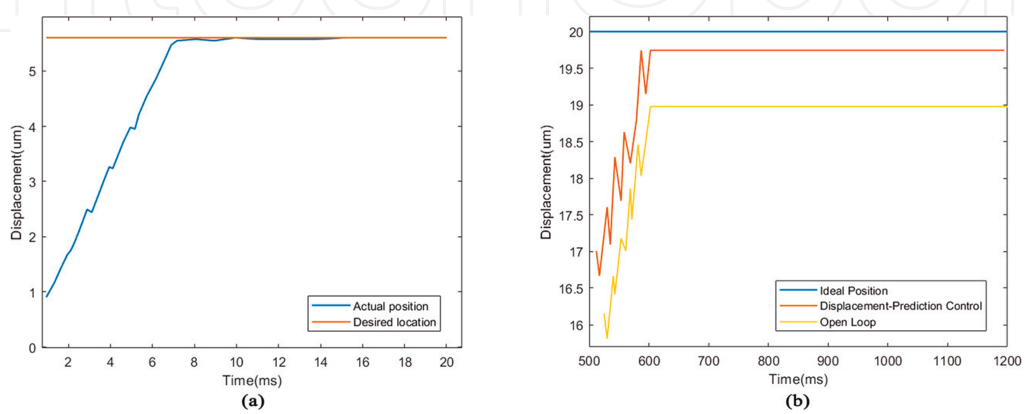

Figure 10.
(a) Simulation of displacement-prediction control positioning performance (target displacement of 20 μm). (b) Comparison between displacement response under the open-loop control and displacement response under the displacement-prediction control (target displacement of 20 μm).

3.3 Intelligent control of piezoelectric stick-slip actuators

By introducing intelligent control algorithms, such as sliding mode control algorithm and neural network algorithm, the self-adjusting control of piezoelectric stick-slip actuator is realized. Closed-loop control with feedback is a common control mode of piezoelectric stick-slip actuators, which can effectively compensate for the effects of hysteresis nonlinearity, complex friction relations and external interference on the positioning accuracy, and improve the robustness of the controller. The closed-loop control is mainly divided into two kinds of closed-loop control. The first closed-loop control is the voltage amplitude of the driving signal, which adjusts the single-step size of the piezoelectric stick-slip actuator by controlling the voltage amplitude. The other is the control of the driving signal frequency. By adjusting the frequency of the piezoelectric stick-slip actuator, the speed of the piezoelectric stick-slip actuator can be controlled. Cao et al. proposed a sliding mode control method based on linear autoregressive proportional integral-differential. It can solve the problem that the hysteretic characteristics of piezoelectric stacks in piezoelectric stick-slip actuators and the nonlinear friction relationship between end-effector and workbench affect the control effect. Firstly, an ARX model of the system is designed, and its state space description is obtained. Then, the sliding mode control is introduced, and PID control is introduced as the frequency switching controller in the sliding mode control, so that the error tends to zero, to achieve better speed control [48].

In addition to introducing the inherent mathematical model into the controller, the controller can also be designed by introducing the neural network algorithm to online model identification. Cheng et al. proposed a neural network-based controller to reduce the effect of complex nonlinearities between the end-effector and the driving object. The structure block diagram of the overall controller is shown in **Figure 11**. The control paradigm of piezoelectric stick-slip actuators is usually divided into two phases—the one-step control phase and the sub-step control phase. In the one-step control phase, when the error between the desired position and the actual position is less than the maximum single-step displacement length by continuous sawtooth wave

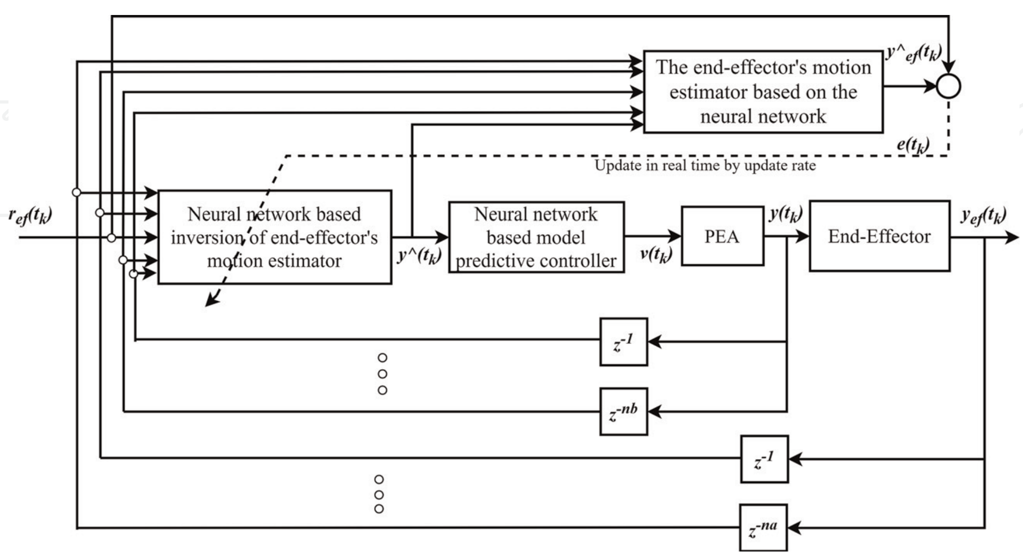

Figure 11.
The schematic of the overall controller in the sub-step control phase—the desired reference $r_{ef}(t_k)$ of the end-effector; the real displacement $y_{ef}(t_k)$ of the end-effector; the estimated displacement $y^{ef}(t_k)$ of the end-effector; the desired displacement $y^{(t_k)}$ of the driving object/PEA; the input voltage $v(t_k)$ applied to the PEA; the real displacement $y(t_k)$ of the driving object/PEA.

excitation, the controller switches to the sub-step control phase. In the experiment, the steady-state tracking error is kept within 50 nm, realizing ultra-precise motion control at the nanometer level [49].

Oubellil et al. applied proportional control to the macro motion control of nanorobots based on the piezoelectric stick-slip motion principle. Under macro motion control, the amplitude and frequency of the sawtooth wave voltage signal are adjusted by proportional control. When switching to scan control mode, Hammerstein dynamic model based on the PI hysteresis model is established, and then H∞ robust control scheme based on the model is designed. The hybrid stepper/scan controller can effectively meet the stability, robustness, hysteresis, and accuracy of multi-target nanorobots [50]. Oubellil et al. also applied piezoelectric stick-slip actuators to the nanorobot system of fast scanning probe microscope. To meet the requirements of fast scanning in closed-loop bandwidth and vibration reduction, the uncertain model of the piezoelectric actuator was defined by the multi-linear approximation method. A 2-DOF H∞ control scheme is designed to provide robust performance for the positioning of the nanorobot system. The fast and accurate positioning of the piezoelectric stick-slip actuator is realized [51].

In addition to its characteristics, the model of piezoelectric stick-slip actuators can also absorb the modeling mode of the piezoelectric stack. In a sense, due to the coupling relationship of the structure, the model can be regarded as an inclusion relation. The control mode of piezoelectric stick-slip actuators can also be the control mode of the piezoelectric stack, such as model-based feedforward control, inversion of control, sliding mode control method, active disturbance rejection control and some intelligent control methods can be applied to the precise control of piezoelectric stick-slip actuators. The research on piezoelectric stack also has reference significance in the precise control of piezoelectric stick-slip actuators.

Sliding mode controller often appears in the control of piezoelectric stack actuators nonlinear system [52, 53]. It is an effective and simple method to deal with the defects and uncertainties of a nonlinear system model. Sliding mode control is not dependent on an accurate mathematical model, which makes it popular in nonlinear system control of piezoelectric actuators. Li et al. proposed a sliding mode controller with disturbance estimation is designed for piezoelectric actuators. The Bouc-Wen model is chosen to describe the input and output relations of the piezoelectric actuator, and a particle swarm optimization algorithm is used for real-time identification of the model parameters. Considering the external and own uncertain disturbances, adaptive control rules are introduced to change the controller parameters. Experimental results show that the proposed controller can significantly improve the transient response speed of the system [54]. Mishra et al. designed a new continuous third-order sliding mode robust control scheme for the hinged piezoelectric actuator. To ensure the overall stability of the closed-loop system, a disturbance estimator was designed to counteract the effects of external disturbances and nonlinearities [55]. Xu Q et al. proposed an enhanced model predictive discrete sliding mode control (MPDSMC) with proportional-integral (PI) sliding mode function and a novel continuous third-order integral terminal sliding mode control (3-ITSMC) strategy [56, 57].

Because of the hysteresis nonlinearity of the piezoelectric actuator and the existence of system vibration and external disturbance, the robustness of the controller is usually required. Wei et al. proposed a variable bandwidth active disturbance rejection control method for piezoelectric actuators. The control method of the nanopositioning system is based on a cascade model of the hysteresis model and the system structure.

Information about all uncertainties and disturbances excluded items in the model is estimated by a time-varying extended state observer (TESO). Afterwards, a variable bandwidth controller based on the control error is designed. Its control system is shown in **Figure 12**. $z1$, $z2$, $z3$are the states of time-varying extended state observer, $b0$ is adjustable coefficient, and d is a disturbance. A series of experiments show that the proposed controller has a higher response speed and stronger anti-interference ability than the traditional active disturbance rejection controller [58].

Neural networks are widely used in the design of adaptive controllers for nonlinear systems because of their strong self-learning ability. In view of the system uncertainty and hysteresis nonlinearity of piezoelectric actuator, Li et al. proposed a neural network self-tuning control method. Two nonlinear function variables about hysteresis output are established and two neural networks are introduced to identify the two hysteresis function variables on line, respectively. Experiments verify that the neural network self-tuning controller has a good track tracking effect [59]. Napole et al. proposed a new method combining super torsion algorithm (STA) and artificial neural network (ANN) to improve the tracking accuracy of high voltage stack actuator [60]. Lin et al. proposed a dynamic Petri fuzzy cerebellar (DPFC) model joint controller for magnetic levitation system (MLS) and two-axis piezoelectric ceramic motor (LPCM) drive system, which is used to control the position of MLS metal ball and track tracking of the two-axis LPCM drive system. The experimental results also show that this method can obtain a high-precision trajectory tracking response [61].

The neural network has a strong self-learning ability and can approach complex nonlinear functions. It plays an important role in the design of the piezoelectric stick-slip actuators controller. In addition to neural network and sliding mode control, data-driven model-free adaptive control is also suitable for systems with model uncertainty. Model-free adaptive control (MFAC) as a typical data-driven control method, this method was proposed in Mr. Hou Z's doctoral thesis in 1994 [62]. In the past two decades, both the continuous development and improvement of theoretical achievements, and the successful practical application in the fields of motor control, chemical industry, machinery and so on, have made MFAC become a new control theory with a systematic and rigorous framework. As for the application of model-free control in the piezoelectric stack, Muhammad designed a data-driven feedforward controller and feedback controller. To avoid chattering caused by noise and affect the convergence of the learning process, several rules about parameters are also proposed. The experimental results show that the controller can realize high-precision position tracking at low frequency [63].

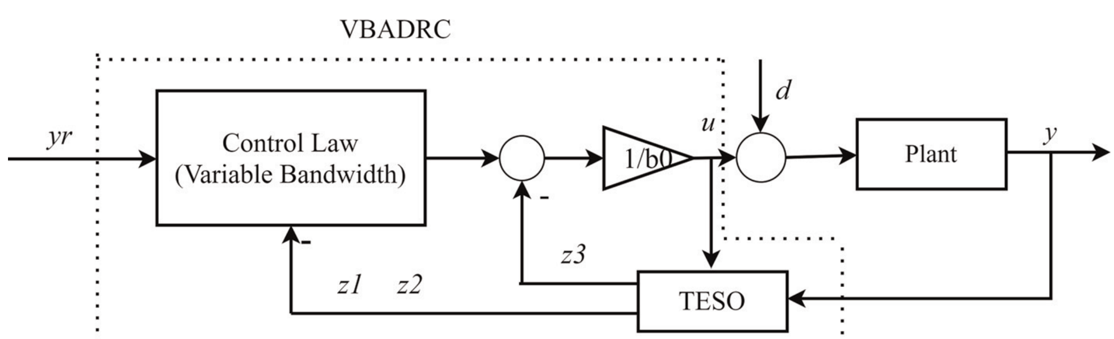

Figure 12.
The variable bandwidth active disturbance rejection control.

4. Conclusions

Piezoelectric stick-slip actuators have great potential in the field of precision operation. However, whether at the experimental level or in the application, the hysteresis nonlinearity of the piezoelectric stick-slip actuator, the complex friction motion relationship in the driving mechanism, its vibration and external disturbance will have a great impact on its motion control accuracy, so that the piezoelectric stick-slip actuator cannot achieve the ideal output performance. In this paper, the modeling and control of piezoelectric stick-slip actuators are summarized and studied.

In the aspect of modeling, the existing mathematical models describing the hysteresis characteristics of piezoelectric stick-slip actuators and the mathematical models of complex friction relationships in the structure are introduced. Hysteresis models mainly include Prandtl-Ishlinskii (PI) model, Krasnosel'skii-Pokrovskii (KP) model, Preisach model, Bouc-Wen model, and Rayleigh model. In terms of the friction model, the existing dynamic friction and static friction models are mainly introduced. The model of piezoelectric stick-slip actuators usually includes the hysteresis model and friction model. In the modeling part, the mathematical model of piezoelectric stick-slip actuators proposed by people is summarized and studied, which provides a reference for the control and model analysis of piezoelectric stick-slip actuators.

In terms of control, according to open-loop control and closed-loop control, this paper summarizes and studies the efforts made by people to make up for control accuracy, and summarizes many control cases, such as feedforward control, sliding mode control, PID control, neural network control, and so on. In the future development of piezoelectric stick-slip actuators, opportunities and difficulties coexist. The control mode can effectively make up for the output performance of piezoelectric stick-slip actuators and make them meet the actual need in various complex environments.

Based on this paper, a more comprehensive dynamics model can be developed in the future by analyzing the characteristics of piezoelectric viscous-slip actuators in-depth to extend to actuators of different mechanical structures. By combining various control methods to eliminate system nonlinearity, higher accuracy and precision motion can be achieved. With the combination of intelligent control field and piezoelectric actuators, piezoelectric stick-slip actuators will be applied to more fields in the future.

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Conflict of interest

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