Modeling and Control of Piezo-Actuated Nanopositioning Stages: A Survey

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***Abstract*—Piezo-actuated stages have become more and more promising in nanopositioning applications due to the excellent advantages of the fast response time, large mechanical force, and extremely fine resolution. Modeling and control are critical to achieve objectives for high-precision motion. However, piezo-actuated stages themselves suffer from the inherent drawbacks produced by the inherent creep and hysteresis nonlinearities and vibration caused by the lightly damped resonant dynamics, which make modeling and control of such systems challenging. To address these challenges, various techniques have been reported in the literature. This paper surveys and discusses the progresses of different modeling and control approaches for piezo-actuated nanopositioning stages and highlights new opportunities for the extended studies.**

***Note to Practitioners*—Piezo-actuated nanopositioning stages featuring fast response, large force, and fine resolution appear poised to play an increasingly important role in fields requiring micro/nano positioning. Such stages, however, exhibit complex piezoelectric behavior, which is often neglected, including: frequency response, nonlinear electric field dependence, creep, aging, and thermal behavior. The presence of such a behavior observed in the stages poses challenges in realizing precise micro/nanopositioning performance. This paper presents an overview of the piezo-actuated nanopositioning stages emphasizing the key role of modeling and control techniques, where high accuracy is important.**

***Index Terms*—Creep, feedback control, feedforward control, hysteresis, piezo-actuated nanopositioning stage, piezoelectric actuator, vibrational dynamics.**

I. Introduction

PIEZO-ACTUATED nanopositioning stages generally refer to flexure-hinge-guided mechanisms driven by piezoelectric actuators, which have been widely applied in precision equipments such as micromanipulators [1]–[5], atomic force microscopes [6]–[10], and ultra-precision machine tools [11]–[13]. They play a vital role for experimental investigation and manipulation of nanoscale biological [14], chemical [15], material [16], and physical processes [17]. During the past decade, various techniques have been applied for modeling and control of such stages to satisfy the critical requirements of different nanopositioning applications [18]. The challenges mainly come from the intrinsic creep and hysteresis nonlinearities of piezoelectric actuators [19], [20] and the lightly damped resonant dynamics behavior of the whole stage [7], [8].

A recent review article has already described the techniques that design the piezo-actuated flexure-guided mechanisms for atomic force microscopes [3], while other surveys have focused on reducing unwanted vibrations of piezoelectric tube scanners with charge control [21] and developments of feedforward control systems for scanning probe microscopes [8]. In this paper, we intend to survey and discuss progresses of different modeling and control approaches for piezo-actuated nanopositioning stages. We also wish to highlight new opportunities that exist for the extended studies.

The remainder of this paper is organized as follows. Section II introduces the system descriptions of the piezo-actuated stage and fully describe its dynamic behaviors. In Section III, various modeling approaches of the piezo-actuated stages are presented and discussed. Subsequently, the control approaches along with the presented models are reviewed. Finally, summary and outlook are provided in Section V.

II. Piezo-Actuated Nanopositioning Stages

A. System Description

Fig. 1 shows a block diagram of the experimental setup of a piezo-actuated nanopositioning stage. Therein, 1) the flexure-hinge-guided mechanism [2]–[5], [11], [22] is usually employed to provide motion by the elastic deformations, which has the advantages of the monolithic structure and no sliding parts, thereby avoiding undesired nonlinear effects such as backlash and friction; 2) the piezoelectric actuator [18], [23], [24] is applied to realize the actuation by generating force on the mechanism due to its excellent advantages of the large output force, high displacement resolution and fast response time; 3) the driver amplifier is used to amplify the control commands for the piezoelectric actuator by either voltage control or charge control methods [25]–[27]; 4) the sensor module consists of a high-resolution sensor and a signal conditioner, where the sensor such as the inductive, piezoresistive, capacitive or optical

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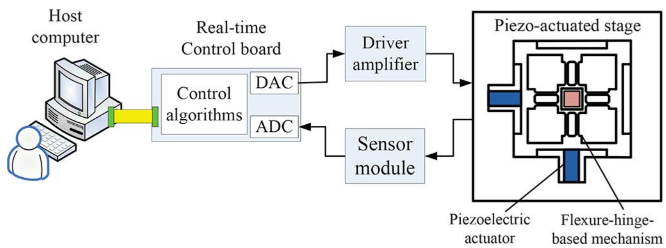


Fig. 1. Block diagram of the experimental setup of a piezo-actuated nanopositioning stage.

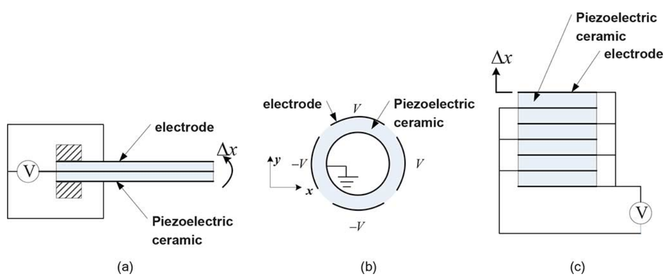


Fig. 2. Diagram of three-type piezoelectric actuators.

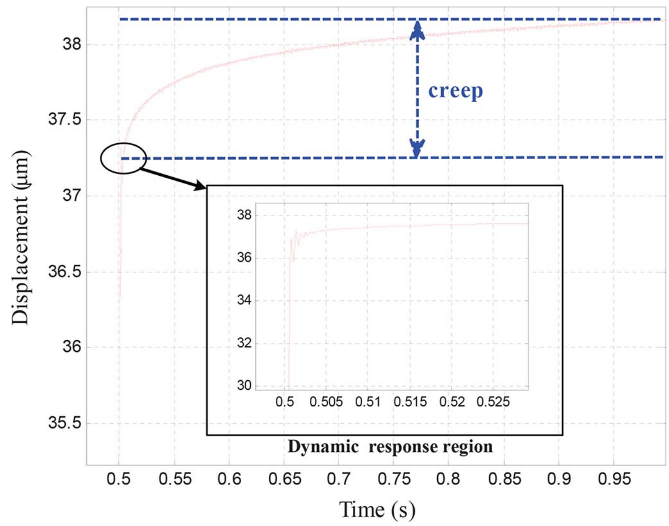


Fig. 3. Creep nonlinearity of a piezoelectric actuator.

sensors [28] is utilized to measure the real-time displacement of the mechanism and the signal conditioner is used to convert the sensor's signals to low-voltage signals for the control systems; 5) the control algorithms are developed and implemented in the real-time control board to produce control commands for the piezoelectric actuator to achieve the nanopositioning motion of the flexure-hinge-guided mechanism.

B. Working Principle

In general, the key enabling element of a piezo-actuated stage is the piezoelectric actuator, which can manage small displacements in the range of subnanometers to several hundreds of micrometers. Therefore, the main advantages of the piezo-actuated stages are due to the utilization of piezoelectric actuators.

The piezoelectric actuator made of piezoelectric materials is a specific type of smart material-based devices that can directly convert an electrical signal into a physical displacement [18], [23], [24]. In the early time, the most applied piezoelectric materials were piezoelectric crystals such as quartz, tourmaline, and Rochelle salt. The discovery of piezoelectric ceramic materials, such as barium titanate and lead zirconate titanate (PZT) brought a major breakthrough owing to their high Curie temperature and outstanding piezoelectric effect [23]. Compared with conventional actuators, piezoelectric actuators can be made smaller and lighter in a variety of forms, ranging from rectangular patches, thin disks, and tubes. In applications, piezoelectric actuators are generally fabricated with three shapes [24], i.e., piezoelectric bender actuators, piezoelectric tube actuators and piezoelectric stack actuators. Fig. 2 shows a diagram of the three types of piezoelectric actuators.

Piezoelectric actuators work on the principle of piezoelectricity, which is an electromechanical coupling phenomenon between electrical properties and mechanical properties of piezoelectric materials [18], [23]. Mechanical stresses in the piezoelectric materials produce measurable electric charge, which is referred to the direct piezoelectric effect. Vice versa, mechanical strains are generated in response to an applied electric field and this is called the inverse piezoelectric effect.

The most famous description of the piezoelectricity was published by a standards committee of the IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society with the linearized constitutive equations as follows [18], [23], [29]:

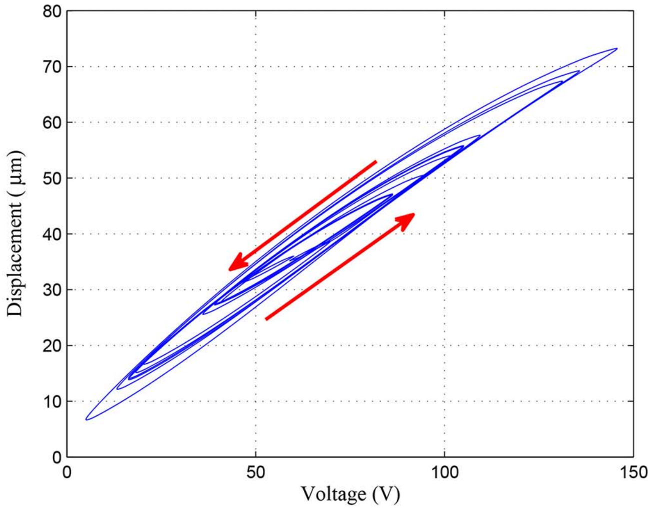
$$\begin{aligned} S_i &= s_{ij}^E T_j + d_{ki} E_k \\ D_m &= d_{mj} T_j + \varepsilon_{mk}^T E_k \end{aligned} \tag{1}$$

where the subscript indexes $i, j = 1, 2, \ldots, 6$ and $m, k = 1, 2, 3$ refer to different directions within the Cartesian coordinate system, S and T represent the strain tensor and stress tensor, respectively, E and D are the electric field vector and electric displacement vector, respectively, s^E is the elastic compliance matrix when subjected to a constant electrical field, d is a matrix of piezoelectric material constants, and ε^T is the dielectric constant matrix under condition of constant stress. The first subscript index of the d-constant gives the "electrical" direction (i.e., field or dielectric displacement), and the second one refers to the direction of mechanical strain or stress.

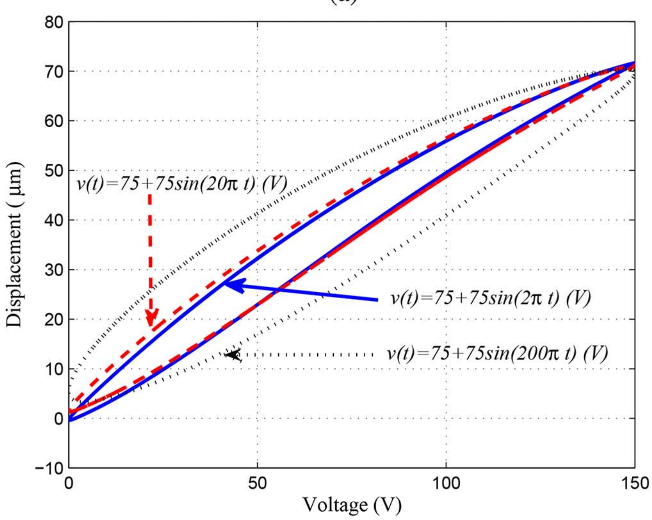
The equations in (1) essentially state that the material stain and electrical displacement are linearly affected by the subjected mechanical stress and electrical field. However, these equations fail to explicitly describe the nonlinearities (such as creep and hysteresis as shown in Figs. 3 and 4) that are presented in piezoelectric actuators and the electromechanical dynamics that are observed in piezo-actuated stages.

C. Modeling and Control Challenges

Through the literature review, the challenges of the modeling and control of piezo-actuated stages arise from the inherent nonlinearities and vibrational dynamics behaviors in the stages, which include the creep, hysteresis and vibration. Interests in understanding these behaviors of the piezo-actuated stages have attracted significant attentions, which are also necessary for development of model-based control techniques to satisfy

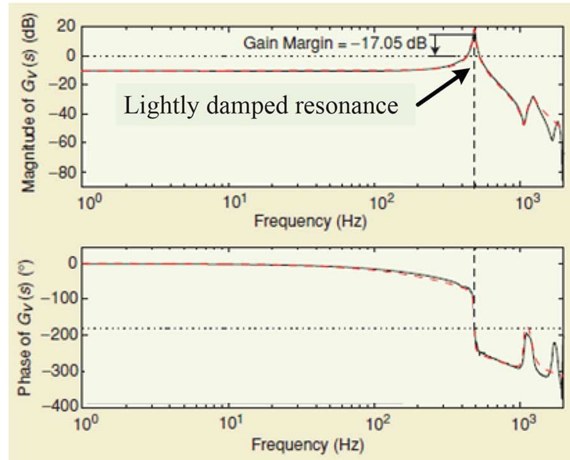


(a)

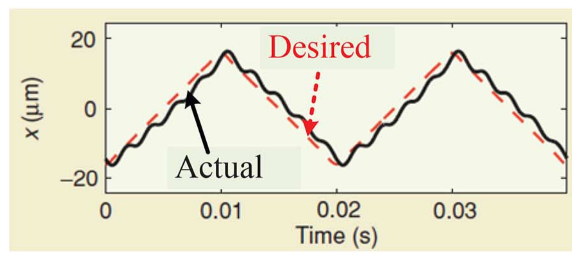


(b)

Fig. 4. Hysteresis nonlinearity of a piezoelectric actuator: (a) amplitude-dependent behavior and (b) rate-dependent behavior.



(a)



(b)

Fig. 5. Vibration effect of a piezo-actuated system. Adapted from [51]. (a) Frequency response. (b) Vibration effect.

the high-precision and high-speed requirements in nanopositioning applications. In the following, the descriptions of these behaviors are discussed first.

1) Creep: Creep is related to the drift phenomenon of the output displacement of the piezoelectric actuator when subjected to an applied voltage [30]–[32], which is an effect due to a slower realignment of the crystalline domains in an applied electric field. The creep effect becomes noticeable over extended periods of time during slow-speed operations. Fig. 3 shows the creep nonlinearity of a piezoelectric actuator when a positive input voltage is applied. It can be seen that large positioning errors are produced with the increase of time after the dynamic response region. On the other hand, a negative step of the applied voltage would have the opposite effect. Generally, this phenomenon can be compensated by the closed-loop control laws such as the proportional integral differential algorithms [33]–[35]. It is pointed out that, in high-speed scanning applications, the creep effect is usually neglected [3], [8]. In slow-speed and open-loop operations of piezoelectric actuators, many efforts [36]–[38] are also made to compensate for the creep nonlinearity.

2) Hysteresis: Hysteresis is the nonsmooth nonlinear phenomenon between the applied voltage and the output displacement of the piezoelectric actuator [39]–[42]. This nonlinearity is multivalued and nonlocal memoryless, which results in the amplitude-dependent behavior, as shown in Fig. 4(a). Therefore, the displacement of the piezo-actuated system depends upon not only the current value but also the previous dominant extrema of the input voltage. In addition, recent experiments have reported that the hysteresis nonlinearity is rate-dependent as well [43]–[46] when the high-frequency input signals are applied to excite the piezoelectric actuators. The hysteresis nonlinearity becomes more evident with the increase of input frequencies as shown in Fig. 4(b). In general, the maximum error caused by the hysteresis can be as much as 15% of the travel range of the piezoelectric actuator. With the increase of frequencies of the input signals, the hysteresis caused errors may go beyond 35%. The hysteresis forms the main impediment to attaining the high-precision performance of the piezo-actuated systems, which leads, in the best case, to reduce the motion accuracy and, in the worst case, to destabilize the control system [47]–[50].

3) Vibration: Vibration is the electromechanical dynamics behavior of the piezo-actuated stages [35], [52]. Due to the characteristics of high stiffness and low structural damping ratio, a sharp peak of the lightly damped resonances emerges in the frequency response of the piezo-actuated stages as shown in Fig. 5(a). The vibrational dynamics have a low-gain margin problem because of the rapid phase drop associated with the

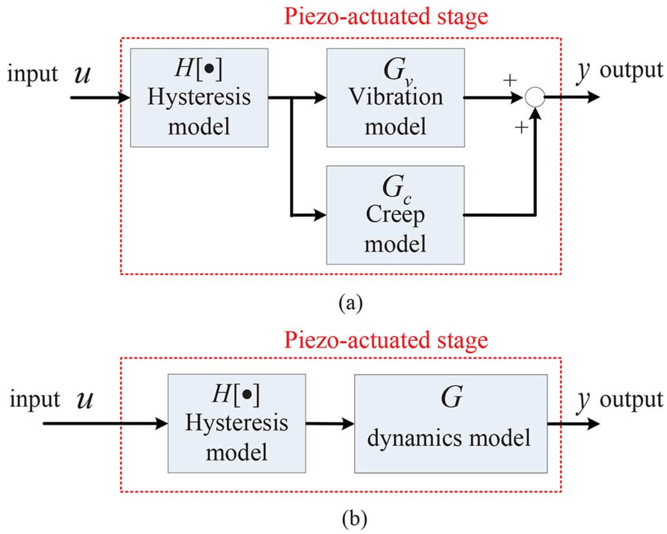


Fig. 6. Block diagram of the cascaded model structure for the piezo-actuated stages. (a) The hysteresis, creep, and vibration are individually modeled as a separated block. (b) The hysteresis is described by H, while the creep and vibration are combined as a dynamics model G.

small structural damping ratio [8] and hysteresis nonlinearity [20]. As a result, input signals with high-frequency components easily excite the oscillation or vibration of the motion as shown in 5(b). Vibration is the main factor limiting the high-speed performance of the piezo-actuated stages [3], [8]. In applications, frequencies of the input signals are restricted to around 1/100 to 1/10 of the lowest resonant modes of the stages [8]. In the early days, the main control objective of the piezo-actuated stages is the tracking precision at low operating speeds [40], [53], where this loss of positioning precision by vibration is generally small. Few research groups pay attentions to suppress the vibration. With the development of nanotechnology, requirements towards increasing the tracking speed of the piezo-actuated stages have come of age [54]–[57], especially in the applications of scanning probe microscopies. In current stage, the number of publications to develop available and efficient techniques for vibration damping have rapidly increased in the last three years.

III. Modeling Approaches

The aim of modeling of the piezo-actuated stages is to develop models that can precisely represent the system behaviors in term of the creep, hysteresis and vibrational dynamics discussed in Section II-C. In the literature, a cascaded model structure with separate blocks depicted in Fig. 6(a) or (b) is generally utilized to characterize the three behaviors. The detailed discussions of the different modeling blocks are presented in this section.

A. Creep Modeling

As depicted in Fig. 3, creep is a slow drift phenomenon after a fast dynamic transient behavior within a few milliseconds. To describe this phenomenon, nonlinear and linear creep models have been proposed.

1) Nonlinear Creep Model: The nonlinear creep model is usually called a logarithmic model, which is inspired by a logarithmic shape of the creep response over time. This model is expressed in the following equation [30], [58]:

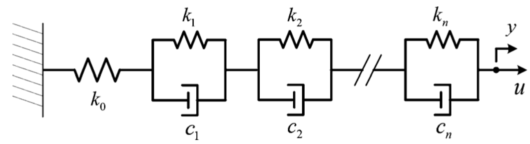


Fig. 7. Viscoelastic creep model. Adapted from [31].

$$y(t) = y_0 \left[1 + \gamma \log_{10}\left(\frac{t}{t_0}\right)\right] \tag{2}$$

where $y(t)$ is the displacement of the piezo-actuated stage when subjected to a fixed input voltage, t_0 is the time at which the creep effect is obvious, y_0 is the displacement at the time of t_0 after applying the input voltage, and γ is a coefficient determining the rate of the logarithmic response. In practice, the values of t_0, y_0, and γ are identified by experimental data of the tested stages [30], [37], [58].

The logarithmic model (2) is a good approximation to describe the creep effect, which has been evidenced in [30], [37], and [58]. The implementation complexity with this nonlinear creep model lies in the fact that the values of y_0 and γ depend on the selection of the time-parameter t_0. Even for a fixed t_0, the value of the parameter γ is still difficult to be determined relying on the history of the past applied voltages [30]. Additionally, the output of the model (2) becomes unbounded as time becomes small (i.e., $t \to 0$) or large (i.e., $t \to +\infty$) enough [18]. These challenges motive researchers to develop other modeling approaches for the creep description.

It is pointed out that a fractional-order modeling approach [59] is recently developed for creep description of the piezo-actuated stages, which results in a double-logarithmic model as follows [59]:

$$\log_{10}(y(t))\,|_{t \geq t_c} = \alpha \log_{10}(t) + \log_{10}\left(\frac{b}{\alpha \Gamma(\alpha)}\right) \tag{3}$$

where t_c is a fixed time, b is a constant, and $0 \leq \alpha \leq 1, \Gamma(\alpha)$ is the gamma function. In [59], the model (3) was demonstrated to fit the experimental data better than the model (2). However, it can be seen that the model (3) is much more complicated than (2) and can only be used when $t \geq t_c$. Therefore, this model (3) is not popular for creep modeling.

2) Linear Creep Model: The linear creep model is a dynamic model to capture the low-frequency response of the piezo-actuated stages [31], [32]. As shown in Fig. 7, a viscoelastic mode with a series connection of springs and dampers [31], is proposed to describe the creep effect, which is expressed in the Laplace domain as follows:

$$G_c = \frac{1}{k_0} + \sum_{i=1}^{N} \frac{1}{c_i s + k_i} \tag{4}$$

where k_0 models the elastic behavior of the PA at low frequencies, k_i represents the spring constant of each spring, c_i refers to the damping constant of each damper, and N is the number of dampers. It should be noted that the same creep model structure (4) is developed in [32], where the creep effect is modeled

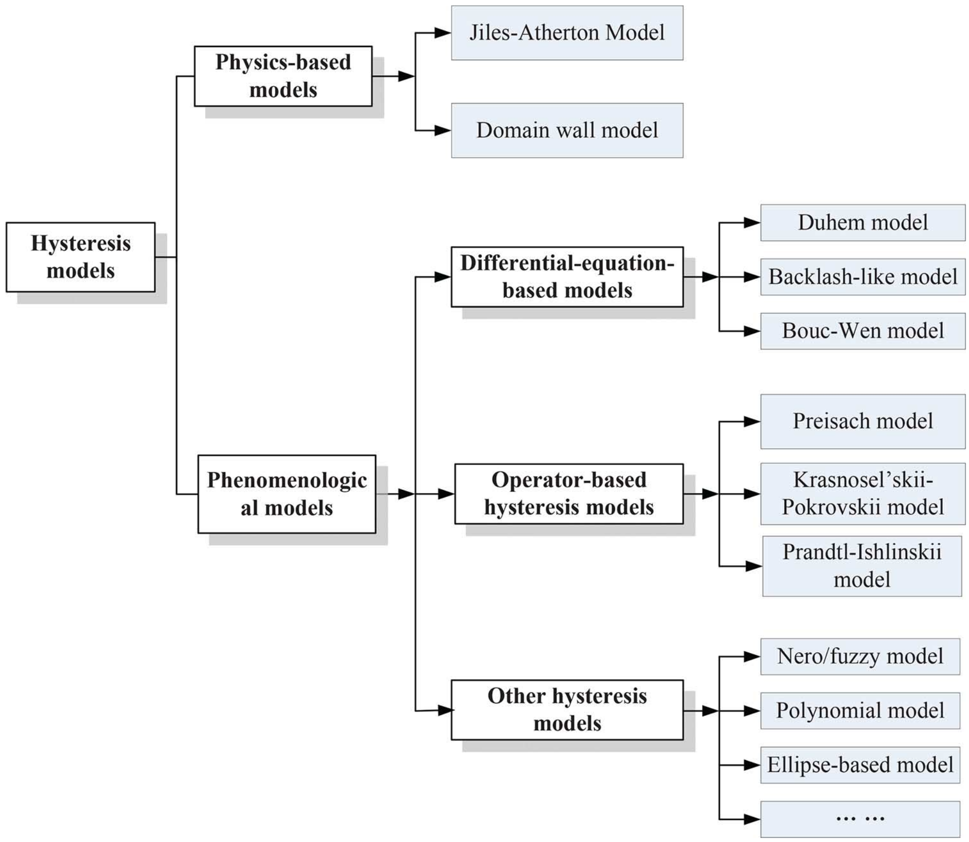


Fig. 8. Category of hysteresis models for piezo-actuated stages.

as an electromechanical model with a weighted sum of *RC* or Voigt–Kelvin circuits in parallel.

The effectiveness of the model (4) described as linear transfer functions has been evidenced in [31], [35], [38]. With the linear creep model (4), the unbounded problem of the nonlinear creep model (2) is avoided. In addition, the creep model (4) can be written as a weighted superposition of many elementary linear creep operators in the time domain, which is convenient to construct an inverse compensator together with the hysteresis compensator based on the Prandtl–Ishlinskii hysteresis model [19], [60], [61].

B. Hysteresis Modeling

The word "hysteresis" is of the Greek origin, which means "lagging behind" or "coming behind." The Scottish physicist, Alfred Ewing, introduced this word into scientific vocabulary as follows [62]: "when there are two quantities M and N, such that cyclic variations of N cause cyclic variation of M, then if the changes of M lag behind those of N, we may say that there is hysteresis in the relation of M and N." As pointed out by Mayergoyz, this may be misleading and can create the impression that the looping is the essence of hysteresis [63]. However, it must not be confused with "delay" or "phase lag," which is not a hard nonlinearity and is present in many linear systems [18]. Hysteresis in the piezoelectric actuator is a special type of memory-based nonlinearity between the input voltage and the displacement of the actuator as addressed in Section II-C2, which becomes the main challenge for high-precision motion control of the piezo-actuated stages.

For treatment of the hysteresis, many efforts have been made in the literature. The first step is generally to develop mathematical models that are sufficiently accurate, amenable to controller design for hysteresis compensation and efficient enough to use in real-time applications [64], [65]. The fact that the complex characteristics of the hysteresis phenomena have probably been the main obstacle on the road towards the development of a standard hysteresis model. As a consequence, a number of hysteresis models are proposed in the literature. Roughly speaking, the reported hysteresis models for piezo-actuated stages can be classified into two categories: physics-based models and phenomenological models. Fig. 8 depicts the categories of these different hysteresis models.

1) Physics-Based Models: Physics-based models are built on first principles of physics effects.

The Jiles–Atherton model is the most famous physics-based model, which was first introduced for ferromagnetic hysteresis [66], [67]. On the basis of the Jiles–Atherton model, Smith and Ounaies [68] proposed a domain wall model for hysteresis description of the piezoelectric actuator with an ordinary differential equation formulation that was amenable to construct an inverse compensator for the linear controller design. The physics-based model is generally very complicated, and the physics-based model developed for one material may not be used for another kind of material.

In contrast, phenomenological models are used to produce behaviors similar to those of physical models without necessarily providing physical insight into the modeling problems [64], [65], [69]. According to the differences of the mathematical structure, phenomenological models for the hysteresis description in the piezo-actuated stages can be classified as differential-equation-based hysteresis models, integral-equation-based hysteresis models (generally called operator-based hysteresis models) and other hysteresis models. It is noted that, nowadays, phenomenological models are more widespread to describe the hysteresis effect of the piezoelectric actuator. In the following, this survey highlights phenomenological models and their applications for control of hysteresis.

2) Differential-Equation Based Models: Differential-equation based models refer to a hysteresis description method in the form of differential equations [39]. As shown in Fig. 8, the Duhem model, Backlash-like model and Bouc–Wen model are popular with differential equations to describe the hysteresis in piezo-actuated stages.

1) **Duhem model**: Since 1897, the Duhem model has been used for hysteresis description [70]. Although it is originally developed to describe the magnetic hysteresis, the Duhem model is also effective to represent the hysteresis in piezoelectric actuators [71], [72].
The Duhem model has the properties that every state is an equilibrium under constant inputs and the output can only change its character when the input changes direction [70], [73]. For suitable functions f_1 and f_2, the Duhem hysteresis model between the input v and output w is expressed as [70]
$$\dot{w}(t) = f_1(w(t), v(t))\dot{v}_+(t) - f_2(w(t), v(t))\dot{v}_-(t) \quad (5)$$
where
$$\dot{v}_\pm(t) = \frac{|\dot{v}(t)| \pm \dot{v}(t)}{2}. \quad (6)$$
In applications, the model (6) can be simplified to a special case given as [70], [74], [75]
$$\frac{dw}{dt} + a\left|\frac{dv}{dt}\right|g(v, w) = b\frac{dv}{dt}. \quad (7)$$
where a typical choice for g is $g(v, w) = w - c\phi(v)$.
2) **Backlash-like model**: based on the simplified Duhem model (7), Su *et al.* [47] developed a Backlash-like model, which was also called as a SSSL model [76]. The Backlash-like model is described as
$$\frac{dw}{dt} = \alpha\left|\frac{dv}{dt}\right|[cv - w] + B_1\frac{dv}{dt} \quad (8)$$
where α, c and B_1 are constant, satisfying $c > B_1$. Following the derivation in [47], the solution of the model (8) is explicitly expressed as
$$w(t) = cv(t) + d(v(t)) \quad (9)$$
with
$$d(v(t)) := [w_0 - cv_0]e^{-\alpha(v-v_0)\mathrm{sgn}(\dot{v})} + e^{-\alpha v \mathrm{sgn}(\dot{v})}\int_{v_0}^{v}[B_1 - c]e^{\alpha\zeta\mathrm{sgn}(\dot{v})}d\zeta \quad (10)$$
for $\dot{v}$ constant, where $w_0 = w(0)$ and $v_0 = v(0)$ are the initial condition, and sgn is the well-known Sign function. The benefit for choosing the Backlash-like model is that the hysteresis nonlinearity is expressed as a linear function of the input signal plus a bounded disturbance. Thus, the conventional robust control approaches can be utilized to deal with the hysteresis without constructing the inverse of the hysteresis [20], [47], [77], [78].
3) **Bouc–Wen model:** on the basis of the Duhem model (5), a hysteretic semi-physical model was proposed initially by Bouc early in 1971 and further generalized by Wen in 1976 [79]. Since then, the Bouc–Wen model has been known and utilized to represent the hysteresis in the form
$$\dot{w} = A\dot{v} - \beta\dot{v}|w|^n - \alpha|\dot{v}||w|^{n-1}w \quad (11)$$
where the parameters A, β, and α are shape parameters of the hysteresis curves. It can be seen from (11) that the input is $\dot{v}$ rather that v although the hysteresis is observed between v and w. The Bouc–Wen model has an interesting simplicity and is able to represent a large class of hysteresis [79]. Because of the elastic structure and material of piezoelectric ceramics, it is generally admitted that $n = 1$ to describe the hysteresis of piezo-actuated stages [80]–[83].

From the above discussions, the differential-equation-based models can be essentially expressed as a first-order differential equation that relates the input to the output in a hysteretic way. In such a way, it can be conveniently augmented by introducing a state variable into the dynamic equations of the piezo-actuated system for controller development [20], [71], [72], [81], [82]. However, it is difficult to obtain the general solutions of differential-equation-based models. On the other hand, until now, there is no method to construct the analytical inverses of the differential-equation-based models for hysteresis compensation.

3) Operator-Based Hysteresis Models: Operator-based hysteresis models are kinds of models with an integral of weighed elementary hysteresis operators [62], [84]–[86]. Based on the differences of elementary hysteresis operators, operator-based hysteresis models for piezo-actuated stages include the Preisach model, Krasnosel'skii–Pokrovkii model and Prandtl–Ishlinskii model as shown in Fig. 8.

1) **Preisach model**: the elementary hysteresis operator in the Preisach model is called Relay. A geometric illustration of the Relay operator $\widehat{\gamma}_{\alpha\beta}[v(t)]$ is shown in Fig. 9. With the Realy operator, the Preisach model is expressed as [62]
$$w(t) = P[v](t) = \int\int_{\alpha\geq\beta}\mu(\alpha,\beta)\widehat{\gamma}_{\alpha,\beta}[v(t)]d\alpha d\beta \quad (12)$$
with
$$\widehat{\gamma}_{\alpha\beta}[v(t)] = \begin{cases} 0, \quad v(t) \leq \beta \\ 1, \quad v(t) \geq \alpha \\ \widehat{\gamma}_{\alpha\beta}[v_0],\ \forall\tau \in [t_0, t], v(\tau) \in (\beta, \alpha) \\ 0,\ \text{if } v(\tau) \in (\beta, \alpha), \exists t_1 \in [t_0, t),\ \text{s.t.} \\ \quad v(t_1) = \alpha \text{ and } \forall\tau \in (t_1, t]v(\tau) \in (\beta, \alpha) \\ 1,\ \text{if } v(\tau) \in (\beta, \alpha), \exists t_1 \in [t_0, t),\ \text{s.t.} \\ \quad v(t_1) = \beta \text{ and } \forall\tau \in (t_1, t], v(\tau) \in (\beta, \alpha) \end{cases} \quad (13)$$

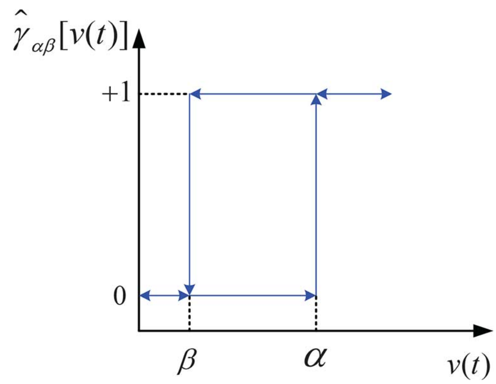


Fig. 9. Geometric illustration of the Relay operator.

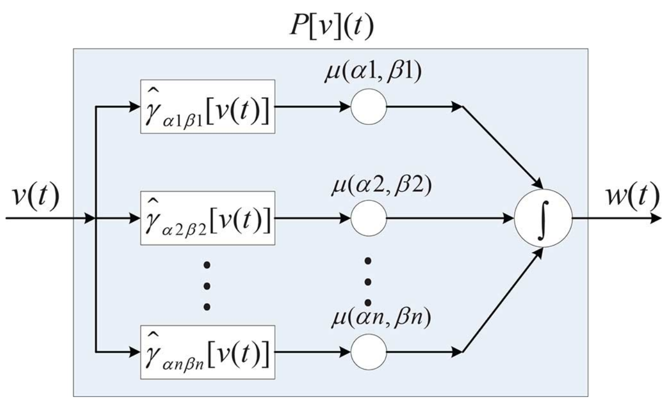


Fig. 10. Block diagram of the Preisach model.

where $\mu(\alpha,\beta)$ is called the density function, and α and β are values of the switching thresholds satisfying $\alpha \geq \beta$. The simple block diagram of the Preisach model (12) is essentially considered as parallel connections of a number of Relay operators as shown in Fig. 10.

The Preisach model was first suggested almost in the 1930s [62], [70]. A thorough discussion of the Preisach model may refer to the Mayergoyz's monographs [41], [84]. The Preisach model can be recognized as a fundamental toolkit of hysteresis modeling for a wide range of hysteresis phenomena because of its general structure [53], [87]–[90]. However, due to the existence of the double integrals, identification and implementations of the Preisach model are usually very complicated [91], [92]. Additionally, the Preisach model is not analytically invertible. Thus, numerical methods are generally adopted to obtain approximate inversions of the model in applications [40], [53], [64], [89], [93]–[96].

2) **Krasnosel'skii-Pokrovkii model**: the elementary hysteresis operator of the Krasnosel'skii-Pokrovkii (K-P) model is called as a KP operator [97], which is a kind of generalized plays [39]. Like the Preisach model, the K-P model is expressed using the double integrals as follows [97]:

$$w(t) = \Lambda[v](t) = \int\int_{\rho_2 \geq \rho_1} \mu(\rho_2,\rho_1) k_p[v,\xi(\rho)](t) d\rho_2 d\rho_1 \tag{14}$$

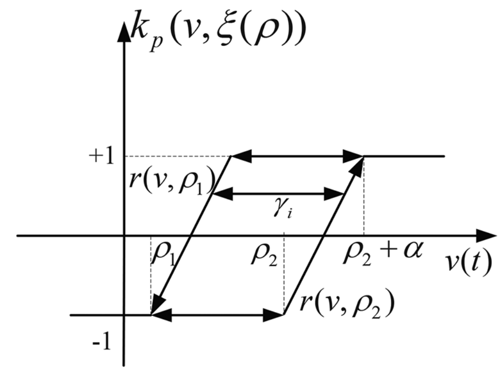


Fig. 11. Geometric diagram of the KP operator.

where $\mu(\rho_2,\rho_1)$ denotes the density function, and ρ_1 and ρ_2 are values of the switching thresholds satisfying $\rho_2 \geq \rho_1$. $k_p[v,\xi(\rho)](t)$ represents the KP operator with the following form:

$$k_p[v,\xi(\rho)](t) = \begin{cases} \max_{\rho \in P}\{\xi_0(\rho), r(v,\rho_2)\}, & \dot{v} > 0 \\ \min_{\rho \in P}\{\xi_0(\rho), r(v,\rho_1)\}, & \dot{v} < 0 \\ k_{p\_}, \quad \dot{v} = 0 \end{cases} \tag{15}$$

with

$$r(v,x) = \begin{cases} -1, & v \leq x \\ -1 + \frac{2}{\alpha}(v-x), & x < v < x+\alpha \\ +1, & v \geq x+\alpha \end{cases} \tag{16}$$

where $\rho = (\rho_1,\rho_2), \alpha > 0, k_{p\_}$ means that the value of the KP operator does not change from its previous value, $\xi_0(\rho)$ is the initial value at location ρ satisfying $-1 \leq \xi_0(\rho) \leq 1$. Fig. 11 shows a geometric diagram of the KP operator $k_p[v,\xi(\rho)](t)$.

It is pointed out that the K-P model is mainly used for hysteresis modeling and compensation in applications with shape memory alloy actuators [98]–[100]. Galinaities [97] investigated the properties of the K-P model and developed an approximate inverse for hysteresis compensation of a piezoelectric stack actuator. Like the Preisach model, the K-P model is also difficult to get an analytical inverse [97], [100].

3) **Prandtl–Ishlinskii model**: The Prandtl–Ishlinskii (P-I) model was originally proposed as a model for plasticity-elasticity [70]. Like the Preisach model, the P-I model is defined by the elementary hysteresis operator called Play or Stop [85], [86]. Different from the discontinuous Relay operator with two thresholds, the Play or Stop is a continuous operator with a single threshold. Fig. 12 shows the geometric diagrams of the Play $(F_r[v](t))$ and Stop $(E_r[v](t))$ operators. Considering the fact that $F_r[v](t) + E_r[v](t) = v(t)$, the P-I model defined by the Play operator is detailed in this survey as an illustration. With a threshold r for any piecewise monotone input function $v(t) \in C_m[0,t_E]$, the Play based P-I model is expressed as [85], [86]

$$w(t) = \Pi[v](t) = p_0 v(t) + \int_0^R p(r) F_r[v](t) dr \tag{17}$$

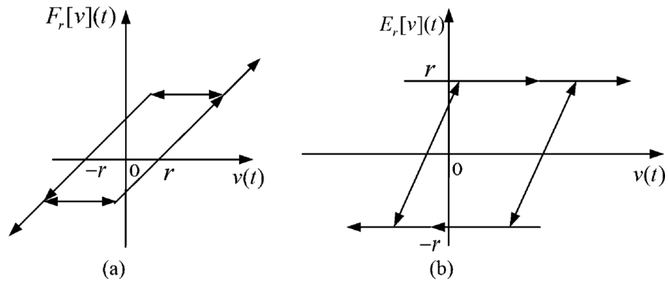


Fig. 12. Geometric diagrams of Play and Stop operators.

with

$$\begin{aligned} w(0) &= F_r[v](0) = f_r(v(0), 0) \\ w(t) &= F_r[v](t) = f_r(v(t), w(t_i)) \end{aligned} \tag{18}$$

for $t_i < t \leq t_{i+1}, 0 \leq i \leq N-1$ with

$$f_r(v, w) = \max(v - r, \min(v + r, w)) \tag{19}$$

where $p(r)$ is a density function and p_0 is a positive constant. The density function $p(r)$ generally vanishes for large values of r, while the choice of $R = \infty$ as the upper limit of integration is widely used in the literature for the sake of convenience [50], [60].

The P-I model (17) is closely linked with the Preisach model (12) even if they seem very different at first glance. As discussed in [64] and [86], the P-I model falls into the set of Preisach model and can be considered as a subclass of the Preisach model. The main advantage of the P-I model over the Preisach model is that the P-I model has the analytical inverse [19], [60], thus making it more efficient for real-time applications. However, the P-I model essentially describes the symmetric hysteresis effect. It fails to characterize the hysteresis effect with the asymmetric behavior observed in the input-output relations of piezo-actuated stages. In an attempt to overcome this limitation, several variations of P-I models for describing the asymmetric hysteresis are reported. Kuhnen [101] proposed dead-zone operators cascaded with the Play operator. Alternatively, Gu *et al.* [50] proposed a modified P-I model with a generalized input function without modifying the Play operator. Instead of using the Play operator, the asymmetric backlash operator [102] was adopted as the elementary operator to represent the asymmetric hysteresis behavir. As another choice, two asymmetric operators [103] were utilized for the ascending and descending branches of hysteresis loops, respectively. Janaideh *et al.* [104] developed two nonlinear envelope function-based operators to form a generalized P-I model for asymmetric hysteresis description. In current stage, interesting in studying P-I model for hysteresis description and compensation in piezo-actuated systems is increasing [49], [50], [91], [105]–[109].

4) **Rate-dependent model**: it is pointed out that the operator-based hysteresis models are by nature developed to describe the hysteresis with the rate-independent memory effect [62], [85], [86], [101]. The rate-independent memory effect of the hysteresis model means that the output of the hysteresis model depends not on the variation rate of the input signals. In some times, the rate-independent effect is also called as the quasi-static behavior, which means the hysteresis output is not affected by the dynamics. In mathematics, the definition of the rate independence can be described by the following [64], [85], [86]: the operator $\aleph$ is defined as rate-independent if and only if the following condition holds:

$$\aleph[x \circ \varphi] = \aleph[x] \circ \varphi \tag{20}$$

with

$$\varphi : t \in [0, t] \to \varphi(t) \in [0, t] \tag{21}$$

where the symbol $\circ$ is the composition operator, $\varphi(0) = 0$ and $\varphi(t) = t$. From the definition of the Relay $\widehat{\gamma}_{\alpha\beta}$ (13) and Play $F_r[v](t)$ (18), Preisach and P-I hysteresis model are intrinsically rate-independent, which can only describe the amplitude-dependent hysteresis as shown in Fig. 4(a). However, the hysteresis in piezo-actuated systems also has the rate-dependent behavior as depicted in Fig. 4(b).

To overcome the limitation for rate-dependent hysteresis descriptions of operators-based models, Mayergoyz [110] developed a rate-dependent Preisach model by introducing the speed of output signals in the density function. Since then, a number of rate-dependent hysteresis models have employed this dynamic density function for characterizing rate dependency of the input-output relationships of piezo-actuated stages. Due to the noise problem for deriving the output signals, Yu *et al.* [111] proposed an alternative method by introducing the variation rate of the input signals to the density function of the Preisach model. Mrad and Hu [112] introduced a time-dependent average rate of change of the input voltage into the Preisach model to account for the rate-dependent hysteresis. With the same idea in [112], Tan *et al.* [113] developed a rate-dependent P-I hysteresis model. Furthermore, Janaideh *et al.* [44] developed a generalized rate-dependent P-I model by modifying not only the density function but also the Play operator with the rate change of the input voltage. As reported, these models [44], [110]–[113] can well predict the rate-dependent behaviors of the hysteresis in piezo-actuated stages. However, owing to the introductions of the derivatives of the input or output signals, the density function and the elementary operators become more complicated, which introduces difficulties in the model identification and real-time controller design for hysteresis compensation.

4) Other Hysteresis Models: In addition to the differential-based and operator-based models, there are some other modeling approaches to describe the hysteresis of piezo-actuated stages.

Intelligent modeling approaches such as artificial neural networks [114]–[116], fuzzy systems [117], [118], and support vector machines [119] have been applied to predict the hysteresis. Additionally, Cruz *et al.* [120] proposed a concept of the apparent phase shift between input and output to describe the hysteresis. The advantage of the concept is that a phaser can be conveniently used to develop hysteresis compensator. Owing

Fig. 13. Schematic representation of different relations in piezo-actuated stages.

to the simplicity of the mathematical description, polynomial function based models [37], [121], [122] were developed to predict the rate-independent hysteresis. Based on the experimental phenomena of the actuator's hysteresis, Gu and Zhu [33], [45] proposed an ellipse-based hysteresis model to characterize the rate-dependent hysteresis of a piezo-actuated stage.

It should be noted that these hysteresis models can precisely and effectively describe the hysteresis of piezo-actuated stages in particular applications, although they are not as popular as the differential-based and operator-based models. On the other hand, it demonstrates that, until now, there is not a general model to completely represent the hysteresis behaviors of piezo-actuated stages.

C. Vibration Modeling

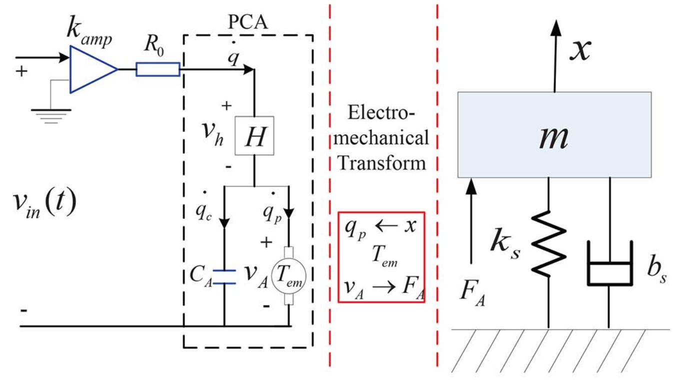
In general, vibration modeling is to develop linear vibrational dynamics models for the piezo-actuated stages without considering the hysteresis nonlinearity [8]. Then, models with linear dynamic equations or transfer function formats are identified by using system identification methods without necessarily providing physical insight into the modeling problems. In this sense, the input and output data of the piezo-actuated stages can be directly used to obtain the linear dynamics models using the commercial dynamic signal analyzer [52], [123], the system identification toolbox in MATLAB [2], [51], [124], the weighted iterative least square fitting technique [125], the subspace-based state space system-identification technique [126], [127], or time-domain-based axiomatic design theory [128]. It is pointed out that the order of the identified dynamics model is determined based on the fitting precision of the identification methods, which is generally high.

D. Comprehensive Dynamic Modeling

Comprehensive dynamic modeling refers to develop an electromechanical modeling method by comprehensively representing the different relations (as shown in Fig. 13) involved in piezo-actuated stages. This method was pioneered by Goldfarb *et al.* [129] and Adriaens *et al.* [130], which was proposed for piezoelectric actuators. Moreover, Gao *et al.* [131] developed a linear modeling approach for the piezo-actuated stage, where the hysteresis effect of the piezoelectric actuator was ignored. Following the accumulated research results in [129]–[132], Gu *et al.* [20] recently developed a general dynamic model for the piezo-actuated stages, including frequency response of the whole electromechanical system, voltage-charge hysteresis and nonlinear electric behavior. Fig. 14 shows the schematic representation of the general model in both electrical and mechanical aspects.

As shown in Fig. 14, the general model is expressed as follows [20]

$$R_0\dot{q}(t) + v_h(t) + v_A(t) = k_{\mathrm{amp}}v_{\mathrm{in}}(t) \tag{22}$$



(a) (b)

Fig. 14. Schematic representation of the general model: (a) electrical aspect; (b) mechanical aspect. Adapted from [20].

$$v_h(t) = H(q) \tag{23}$$
$$q(t) = q_c(t) + q_p(t) \tag{24}$$
$$v_A(t) = q_c(t)/C_A \tag{25}$$
$$q_p(t) = T_{\mathrm{em}}x(t) \tag{26}$$
$$F_A = T_{\mathrm{em}}v_A(t) \tag{27}$$
$$m\ddot{x}(t) + b_s\dot{x}(t) + k_s x(t) = F_A \tag{28}$$

where v_{in} is the control input to the driving amplifier, k_{amp} is the fixed gain of the amplifier, R_0 is an equivalent internal resistance of the driving circuit, q is the total charge in the piezoelectric actuator and the resulting current flowing through the circuit is $\dot{q}, v_h$ is the generated voltage due to the hysteresis effect H, T_{em} represents the piezoelectric effect that is an electromechanical transducer, C_A represents the sum of the capacitances of the total piezoelectric ceramics in the actuator, q_c is the charge stored in the linear capacitance C_A, q_p is the transduced charge from the side due to the piezoelectric effect, v_A is the transduced voltage, F_A is the transduced force from the electrical side, x is the output displacement of the mechanism part, m, b_s, and k_s are the equivalent mass, damping coefficient, and stiffness of the moving mechanism, respectively.

To present $v_A(t)$ in (27) in terms of $q(t)$, the dynamic equation (28) can be rewritten as

$$m\ddot{x}(t) + b_s\dot{x}(t) + \overline{k_s}x(t) = \frac{T_{\mathrm{em}}}{C_A}q(t). \tag{29}$$

where $\overline{k_s} = k_s + (T_{\mathrm{em}}^2)/(C_A)$. From (29), one can observe that the hysteresis effect does not play a role, which indicates that the charge control of piezoelectric actuators can eliminate the hysteresis effect. The effectiveness of the charge control for mitigating the hysteresis of piezoelectric actuators have been well verified by the experiments [25]–[27].

In case of voltage control, the dynamic electromechanical model from (22)–(28) is derived in the following

$$R_0C_A\dot{q}(t) + q(t) - T_{\mathrm{em}}x(t) = C_Ak_{\mathrm{amp}}\left[v_{\mathrm{in}}(t) - \frac{H(q)}{k_{\mathrm{amp}}}\right] \tag{30}$$

$$m\ddot{x}(t) + b_s\dot{x}(t) + \overline{k_s}x(t) = \frac{T_{\mathrm{em}}}{C_A}q(t) \tag{31}$$

It is pointed out that the general dynamic model (30) and (31) can be reduced to other developed models in [129]–[132]. The detailed notations and discussions may refer to [20].

With the developed model (30) and (31), there are two approaches to represent the dynamics behaviors of piezo-actuated systems for designing and implementing control strategies in the literature. The first approach is to treat the term $v_{\text{in}}(t) - (H(f(v_{\text{in}}))/(k_{\text{amp}})$ as a new hysteresis nonlinearity, and a cascaded structure with a linear dynamic model preceded by a hysteresis model [as depicted in Fig. 6(b)] is obtained [20], [49], [72], [105], [133]–[136]. The second one is by assuming $R_0 = 0$; the complete model is described by $m\ddot{x}(t) + b_s\dot{x}(t) + k_s x(t) = T_{\text{em}}[k_{\text{amp}} v_{\text{in}}(t) - H(q)]$ with a nonlinear hysteresis term [81], [137]–[140]. For different approaches, the treatment for the controller designs is quite different because the hysteresis term in the first can be regarded as a preceding component while the second is as a sum component. The detailed control approaches will be discussed in Section IV.

IV. Control Approaches

The aim of control the piezo-actuated stages is to satisfy the nanopositioning requirements of different applications by designing effective control algorithms to remedy the undesirable behaviors, i.e., the creep, hysteresis, and vibration, as discussed in Section II-C. However, precision control of piezo-actuated stages is a complicated task due to the inherent nonlinearities of piezoelectric actuators and their strong coupling with the dynamics of the stages. Especially, it is well known that the hysteresis nonlinearity gives rise to undesirable inaccuracy or oscillations, even leading to instability of the systems, which is quite challenging to design effective controllers to remedy the hysteresis in the area of control system research as well [47], [48], [141]–[144].

Over the past decades, various control approaches have been developed for piezo-actuated stages. Through the literature review, these approaches can be roughly classified into feedforward control, feedback control and feedforward-feedback control. As an illustration, when the piezo-actuated stages are described as a cascaded model shown in Fig. 6(b), the control block with the three approaches are depicted in Fig. 15.

The feedforward control approach as shown in Fig. 15(a) is most commonly used in the literature, where the corresponding inverse compensators with different models addressed in Section III are placed in the feedforward loop to compensate for the undesirable behaviors.

In the feedback control approach as shown in Fig. 15(b), the hysteresis nonlinearity is either directly treated as a nonlinear bounded disturbance or characterized by the hysteresis models (as detailed in Section III-B) that are usually divided into a linear term multiplying the control action and a bounded disturbance-like nonlinear term. In this way, available control methods are able to deal with the non-smooth hysteresis nonlinearity and different feedback control techniques are proposed for high-precision control of the piezo-actuated stages.

By combining the feedforward and feedback control approaches, the feedforward-feedback control category is shown in Fig. 15(c). In this category, the inverse compensators with different models are applied in the feedforward path and the

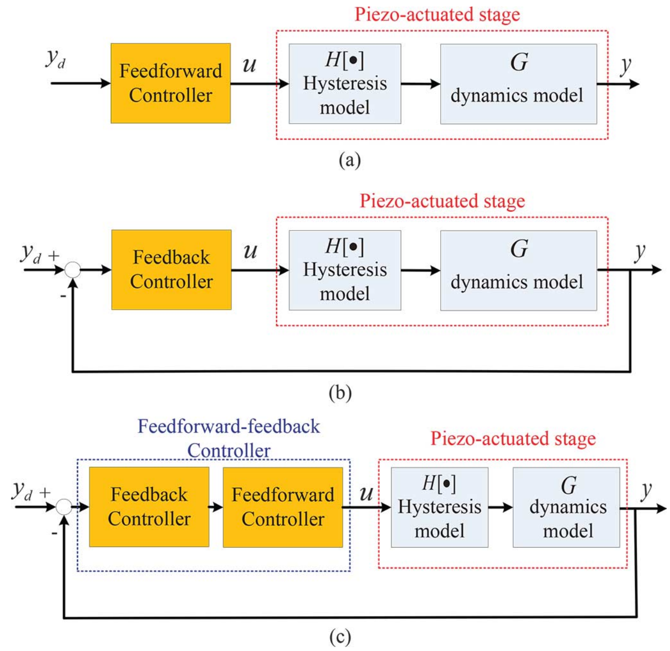


Fig. 15. Three kinds of control approaches for piezo-actuated stages (y_d denotes the desired command; u denotes the output of the designed controller; y denotes the actual reponse of the stages).

feedback controllers are simultaneously designed in the feedback loop to mitigate the effect of the inversion errors and to handle the remaining dynamics of the systems.

In the following, reviews on the three control approaches for piezo-actuated nanopisitioning stages shall be detailed and discussed.

A. Feedforward Control

Feedforward control is effective to improve the control performance of piezo-actuated stages, which uses the known system dynamic models to design an control input [8]. In the literature, a number of publications are reported to compensate for the creep, hysteresis and vibration, respectively.

1) Feedforward for Creep: The feedforward inverse of the creep can be constructed by either the nonlinear model (2) or the linear model (4). Using the nonlinear creep model (2), Jung *et al.* [145] developed an inverse based on a concept of voltage creep. Using the linear creep model (4), Rakotondrabe *et al.* [38] developed the observer-based feedforward compensator for inverse creep compensation. In the time domain, the linear creep model (4) can be represented by superpositions of fundamental creep operators and a term proportional to the input. The benefit for such a description is that the creep operators can be integrated with the P-I hysteresis model to construct the analytical inverse for both the creep and hysteresis compensation [19], [60], [61].

It is pointed out that, when the piezo-actuated stages are controlled with the feedback loops, it is generally not necessary to implement the feedforward controller for the creep compensation since the creep can be easily mitigated by a traditional feedback controller, such as a conventional proportional integral differential (PID) controller [18], [33]–[35], [124]. Thereafter, the control challenges of piezo-actuated stages mainly lie in compensating for the hysteresis and vibration.

2) Feedforward for Hysteresis: Owing to the complex characteristics of the hysteresis nonlinearity, the feedforward control technique is the common approach for dealing with this nonlinearity, i.e., constructing a controller by putting in cascade as a compensator to cancel the hysteresis effect [65]. In applications, there are generally two steps to develop feedforward hysteresis compensators. The first step is to find an available hysteresis model (referring to Section II-B) that can precisely describe the hysteresis. The second step is to develop a feedforward controller according to the selected hysteresis model. To this end, three different approaches are reported in the literature.

The first approach is the most widely used one that is required to construct an inverse of the adopted hysteresis model. Upon the various hysteresis models discussed in Section II.B, construction of inverse functions of the hysteresis model is mainly for operator-based models i.e., the Preisach and P-I models. When the hysteresis is represented by differential-based models such as the Duhem model, Backlash-like model and Bouc-Wen model, the inverse construction is either impossible or extremely difficult to be obtained. It is pointed out that the Preisach model is not analytically invertible. Therefore, numerical methods are generally adopted to obtain approximate inversions of the Preisach model using table-lookup procedure or iterative algorithms [40], [53], [64], [93]–[96]. Alternatively, adaptive algorithms [89], [143] can also be used to effectively approximate the inverse of the Preisach model for hysteresis compensation. In this case, the hysteresis is approximately compensated by implementing a Preisach model-based inverse as a feedforward compensators. Although this approach has shown good results in the literature, it is very difficult, if not impossible, to demonstrate the stability of the resulting closed-loop system with the Preisach model. Comparing with the Preisach model, the P-I model has the advantage of the analytical inverse. Krejci and Kuhnen [60] first provided the analytical inverse of the classical P-I model and extensive works have then been developed in [48], [50], [101], [104], [146], [147]. Additionally, other hysteresis models based on the neural network [114], phaser [120], polynomial function [37], [121], and ellipse [33], [45] were also applied to construct inverse model for the hysteresis compensation.

The second approach is to directly use the adopted hysteresis models to develop the feedforward compensators, for which the aim is not for the development of inversions for the hysteresis models themselves. Rakotondrabe [82] developed a feedforward compensator with the Bouc–Wen model based on the multiplicative-inverse structure. Rakotondrabe also extended the multiplicative-inverse structure for the hysteresis compensation of the piezoelectric actuator based on the classical P-I model [148]. In [71], Lin utilized the generalized Duhem model to achieve feedforward compensation of the hysteresis in a biaxial piezo-actuated stage. In [83], Xu developed a least squares support vector machine-based hysteresis model for both purposes of hysteresis identification and hysteresis compensation. Comparing with the first approach, the second approach avoids the complicated procedure for constructing inverse functions of the hysteresis models. However, this second approach may not be applicable to some hysteresis models such as the Jiles-Atherton model and Krasnosel'skii–Pokrovskii model.

The third approach is based on the direct inverse hysteresis compensation concept [91], which directly utilizes the available hysteresis models to describe the inverse hysteresis effect rather than modeling the hysteresis effect. This concept is motivated by the fact that the inversion of the hysteresis effect is by nature hysteresis loops. The difference between the inverse hysteresis and the real hysteresis in piezoelectric actuator is the orientation of the hysteresis loops. With this concept, Devasia *et al.* [31] adopted the Preisach model to directly model the inverse hysteresis effect. Gu *et al.* [35], [91] utilized a modified P-I model for asymmetric hysteresis compensation. The same idea with the P-I model have also been reported in [49], [106]. It is pointed out that only approximated compensation can be expected with the third approach.

3) Feedforward for Vibration: The common idea of feedforward development for compensating the vibration without considering the hysteresis is by nature a model-based control method by inverting the linear dynamic model of the piezo-actuated stages. In this subsection, we give a brief review of the feedforward control for vibration compensation. The reader may refer to [8] for detailed discussions.

For the linear dynamic model described as G, the inverse input $U_{ff}(\cdot)$ is expressed as $U_{ff}(\cdot) = G^{-1}[P_d(\cdot)]$ with the desired output trajectory $P_d(\cdot)$. Such feedforward inversions include: 1) dc-gain inversion; 2) exact inversion; 3) optimal inversion; and 4) periodic inversion.

The dc-gain inversion is the simplest feedforward input $u_{ff}(t) = G(0)^{-1}p_d(t)$, which has been used in [149]. However, the dc-gain inversion causes significant vibration and positioning errors as the fundamental frequency in $p_d(t)$ is increased [8].

The exact inversion can be obtained for the minimum-phase G using the transfer function approach

$$U_{ff}(s) = G^{-1}(s)P_d(s). \tag{32}$$

According to (32), $u_{ff}(t)$ in the time domain can be directly obtained by the inverse Laplace transform. In [150], [151], the exact inversions were obtained in a state-space form and used to compensate for vibration of piezo-actuated scanners. However, the exact inversion cannot be used for the nonminimum phase systems $G(s)$ due to the unstable nature of $G^{-1}(s)$.

To overcome the limitation of the exact inversion, the stable inverse can be obtained using the Fourier transform approach [52]

$$U_{ff}(j\omega) = G^{-1}(j\omega)P_d(j\omega). \tag{33}$$

According to (33), $u_{ff}(t)$ in the time domain can be directly obtained by the inverse Fourier transform. Using this approach, the optimal inversions [8], [31], [52] were found by minimizing the designed cost function that was similar to the cost function used in standard linear quadratic regulators with frequency-dependent weights.

The periodic inversion is developed to compensate for vibration when a desired trajectory is periodic. The periodic inversion can be expressed as

$$u_{ff}(t) = \frac{B}{G(0)} + \sum_{k=1}^{\infty} \frac{A_k}{|G(i\omega_k)|} \sin(\omega_k t - \phi_k) \tag{34}$$

where $p_d(t) = B + \sum_{k=1}^{\infty} A_k \sin(\omega_k t),\ k = 1, 3, 5, 7, 9, \ldots$, and $\phi_k = \angle G(i\omega_k)$. The input (34) has been successfully applied to develop feedforward controllers for vibration compensation of piezo-actuated systems [5], [8], [152].

Alternatively to the inversion based method, input-shaping and notch-filter methods could also be adopted as feedforward to compensate for vibration. In [82], [123], [153], the input shaping methods were used to minimize the excitations of the resonant modes. In [34], [35], notch filters were designed to damp the resonant modes. The main advantage of input-shaping and notch-filter methods is that the simple knowledge of the resonance frequency and damping ratio of main resonant modes is sufficient to compensate for the vibration without the need to model the full system dynamics.

It is pointed out that the feedforward control approach cannot be used to correct for the positioning errors caused by model uncertainties and external disturbances [8]. In general, feedback control approaches will be used to reduce the effects of uncertainties and disturbances discussed in the following.

B. Feedback Control

Feedback control that uses the real-time information about the measured output is a powerful technique to guarantee tracking performance of systems in the presence of nonlinearities and unmodeled dynamics.

The utmost importance in feedback control systems is the stability. In fact, development of feedback controllers for dynamics systems with hysteresis nonlinearity is challenging [47], [69], [77], [108], [133], [154]–[160], especially when the hysteresis is unknown, which is a typical case in practical applications. Through the literature review, there are two methods to design the feedback controllers for piezo-actuated stages, which can be distinguished by whether the hysteresis models are utilized in the control design. Without using the hysteresis models, the first method is to directly develop the feedback controllers, where the hysteresis is usually treated as a bounded nonlinear disturbance to guarantee the stability. In the second method, it is by nature to find the hysteresis models as addressed in Section II-B, which can describe the hysteresis behaviors and then be utilized for control design to mitigate the effects of hysteresis. In this case, to design a feedback controller with guaranteed stability for the dynamics system affected by the hysteresis, the general approach is to decompose the adopted hysteresis models into two terms including the linear term multiplying the control action and a bounded disturbance-like term.

With its three-term functionality covering treatment to both transient and steady-state responses, PID control offers the simplest solution and yet most efficient solution in industrial applications [161]. In this sense, various PID controllers including integral controllers [3], proportional integral controllers [162], [163], and PID controllers [164] have been widely applied for control of commercial piezo-actuated stages. To real-time tune the gain parameters, automated tuning PID controller [165] and dynamic PID controller [166] have been reported. Treating the hysteresis nonlinearity as disturbances, the disturbance observe-based PID controller [72] and the nonlinear PID controller with the extended state observer [167], [168] have also been developed to improve the performance of PID controllers. However, it remains a challenge to achieve the desired performance. By interpreting the Preisach hysteresis model as a phase shift, a linear lead controller was proposed to compensate for this phase lag [120]. In addition, the pole-zeros cancellation [169] and state feedback control techniques with observers [124] were developed when the hysteresis effect was not considered in the feedback design. It is pointed out that these PID-based control laws or state feedback controllers can generally be used to control piezo-actuated stages at low frequencies or under a small travel range due to fundamental limitations on their tracking bandwidth and effectiveness to handle the hysteresis nonlinearity in trajectory tracking applications.

To overcome such limitations, recent research efforts have gone into designing control laws with modern control techniques such as repetitive control, H_∞ control, sliding mode control, and adaptive control. The main challenge in feedback designs with modern control techniques is performance improvement while maintaining the stability of the overall system in the presence of model uncertainties and hysteresis nonlinearity [7], [8]. With the hysteresis nonlinearity described by the Maxwell slip model [170] or the P-I model [49], repetitive controllers were designed to enhance the tracking performance of piezo-actuated systems with periodic desired references. By treating the hysteresis as a disturbance, H_∞ controllers [58], [135], [138] and gain scheduling controller [171] were designed. With an emphasis on the hysteresis using a bounded delay and gain, a Smith predictor-based H_∞ controller [172] was developed to achieve high-precision tracking control of a piezo-actuated stage. Owing to its ease of design and robustness for the unknown disturbances, sliding mode control is another popular robust control approach for piezo-actuated stages [139], [173]–[177]. However, the knowledge of parameter variation range of the system model is usually needed to ensure stability and satisfy reaching conditions, which may involve infinite-gain feedback. To overcome the drawback of the sliding mode control, adaptive control [133] is generally introduced to estimate the system parameters. In this sense, robust adaptive controllers integrating both the sliding mode control and adaptive control approaches guarantee a superior performance in terms of both the transient error and the final tracking accuracy in the presence of both parametric uncertainties and uncertain nonlinearities. The advantages of the robust adaptive controllers for high-performance motion control of piezo-actuated systems have been well verified through recent studies [20], [81], [134], [136], [178]–[180]. Additionally, the model predictive sliding mode control scheme by combining the advantages of the model predictive control and sliding mode control has been reported to improve the positioning performances of piezo-actuated stages [137], [181]. Attempts have also been made to use intelligent control techniques such as neural network control [182]–[184], fuzzy control [185], [186], and iterative control [187], [188] for high-precision tracking control of piezo-actuated stages owing to their representative properties and capabilities including input-output mapping or universal function approximation for nonlinear systems. Alternatively, passivity approaches have been applied

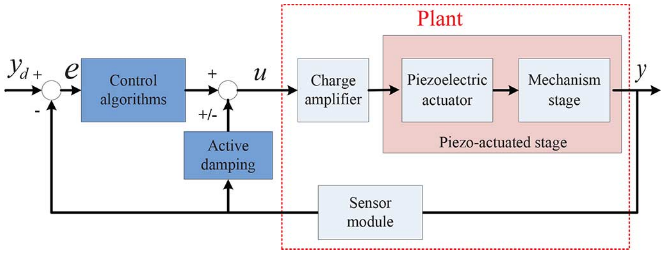


Fig. 16. Block diagram of the feedback control with an active damping controller.

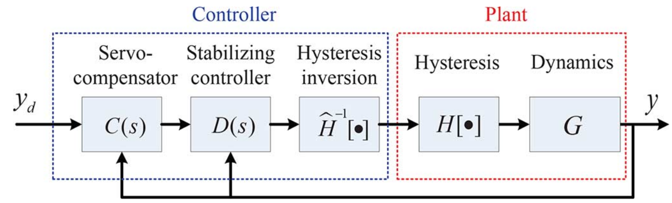


Fig. 17. Block diagram of the servocompensator/stabilizing controller followed by an approximate inverse compensator for hysteresis. Adapted from [105].

for stability analysis and control design for systems with the Preisach hysteresis model [142] (without system dynamics) or Duhem hysteresis model [189].

The advantages of feedback control include: 1) the ability to handle modeling uncertainties and nonlinearities and 2) the robustness to parameter variations and disturbances. However, uncertainties in the system models together with the complex nonlinear behaviors, especially the hysteresis nonlinearity, make it difficult to obtain robust stability results. Additionally, the tracking performance will degrade at high frequencies since the feedback controller gains cannot be chosen to be sufficiently high at those frequencies due to the drawback of the low gain margin vibrational dynamics [8], [58].

When the charge control [25]–[27] is used to reduce the hysteresis nonlinearity of the piezoelectric actuators, to tackle the unwanted vibrational dynamics, active vibration or damping control has been proven to be effective for piezo-actuated stages [3], [21]. In the literature, positive position or velocity feedback [57], [190], polynomial-based controller [190], delayed resonant control [191] and integral resonant control [149] have been developed. Fig. 16 shows the block diagram of the feedback control scheme with an active damping controller.

As another choice, feedforward control combined with the feedback control can be designed and implemented to enhance the tracking performance of the feedback controllers, which will be detailed in the following subsection.

C. *Feedforward-Feedback Control*

Combining the advantages of the feedforward and feedback control, feedforward-feedback control is usually applied for high-precision and high-speed control of piezo-actuated stages. It is pointed out that, as discussed in Section IV-A1, the creep phenomenon can be easily mitigated by the traditional feedback control approaches such as the PID controllers [18], [33]–[35], [124]. It is generally not necessary to develop the feedforward controller for the creep compensation in the feedforward-feedback control approach. Therefore, according to the differences in the feedforward controllers, there are three kinds of feedforward-feedback control schemes for piezo-actuated nanopositioning stages: 1) feedforward controllers only for the hysteresis compensation; 2) feedforward controllers only for the vibration compensation; and 3) feedforward controllers for both the hysteresis and vibration compensations.

In the first kind of feedforward–feedback control scheme, the feedforward controllers are developed for the hysteresis compensation. As pioneered in [40], the inverse hysteresis compensator with the Preisach model was developed to compensate for the hysteresis and a PID controller was adopted to correct for the creep nonlinearity and modeling uncertainties. Similar to the control scheme in [40], extensive works have then been developed by combining different hysteresis models for feedforward compensators (detailed in Section IV-A2) and different control strategies (detailed in Section IV-B) for feedback loops [18], [49], [53], [109], [119], [192]–[194]. It is pointed out that, in this control scheme, the hysteresis is generally approximately compensated and a feedback controller is designed to reduce residual error due to inaccurate hysteresis model inversion and the system uncertainties. Although this approach has shown good results in the experiments, the experimental results depends on the identified parameters and it is generally very difficult, if not impossible, to demonstrate the stability of the resulting closed-loop systems. By modeling the plant as a linear dynamic model preceded by the P-I hysteresis model, a servocompensator/stabilizing controller in combination with an approximate hysteresis inverse as shown in Fig. 17 was recently developed, where the closed-loop system admitted a unique and asymptotically stable periodic solution [105]. Although the solution in [105] is limited to tracking periodic signals, it is of interest to understand the impact of modeling errors on the tracking performance of the piezo-actuated stage.

In the second kind of feedforward-feedback control scheme, the feedforward controllers are developed for the vibration compensation. In this control scheme, the notch filter [34], [35], [55], [195], input-shaping controller [153] and inversion-based controller [5], [125], [196]–[198] are usually developed. As discussed in Section IV.B, it is generally difficult to obtain robust stability results due to the fact that the complex hysteresis nonlinearity in most of applications cannot be just assumed as a simple disturbance. With this feedforward-feedback control scheme, a so-called “impulsive control” approach [9] based on modifications of controller states at discrete time instances was recently proposed to fast nanopositioning of the piezo-actuated scanner. Fig. 18 shows the schematic block of the feedforward-feedback control scheme based on impulsive state multiplication, where the feedback controller (K_{FB}) is subject to instantaneous multiplicative state changes at discrete time instants, driven by the impulsive state multiplication (ISM) control law [9].

Combining the first and second schemes, the feedforward controllers in the third kind of feedforward-feedback control scheme are developed for both the hysteresis and vibration compensations. With such a control scheme, many works [35], [146], [192], [199], [200] have been recently reported for

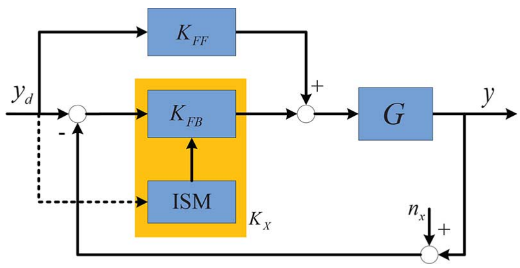


Fig. 18. Block diagram of the feedforward-feedback control scheme with the ISM. Adapted from [9].

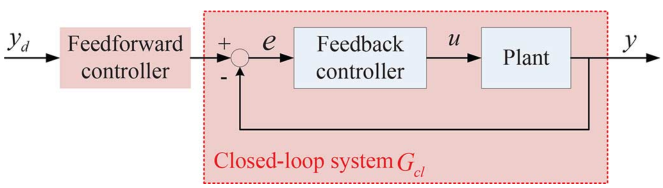


Fig. 19. Block diagram of the feedforward-feedback control scheme with the closed-loop inversion. Adapted from [18].

high-bandwidth control of piezo-actuated stages. It is pointed out that this control scheme usually first places an inverse hysteresis compensator in the feedforward loop to perform hysteresis cancelation, then adopts a resonant controller to damp the vibrational dynamics, and finally designs a feedback controller to minimize the tracking errors.

Fig. 19 shows another feedforward-feedback control architecture involving feedforward and feedback control reported for piezo-actuated nanopositioning stages. Different from the feedforward controller designed with the dynamic model of the plant shown in Fig. 15(c), the feedforward controller in this architecture shown in Fig. 19 is a closed-loop inversion by inverting the dynamic model of the whole close-loop system. Comparisons of the two control schemes have been discussed in [201]. This closed-loop inversion reduces the computational error as the uncertainties and nonlinearities are compensated in advance by the feedback control loop. Various stable closed-loop inversion approaches such as zero-phase-error tracking controllers [202], zero-magnitude-error tracking controllers [201], [203], pre-filters [125], [152], [204] have been developed for piezo-actuated stages. It is noted that although the control bandwidth can be improved with the closed-loop inversion, the low-gain margin problem in designing feedback controllers still exists in this feedforward-feedback control architecture [18].

V. Summary and Outlook

Piezo-actuated nanopositioning stages are becoming more and more promising with the rapid development of nanomeasurement, nanofabrication and ultra-precision manufacturing. Control is urgent and critical to achieve the nanopositioning objectives in these applications. In general, system models are important to understand the dynamic behaviors of the piezo-actuated stages and to develop various model-based control approaches. Considering the dynamic behaviors of piezo-actuated stages in terms of hysteresis, creep and vibrational dynamics, this paper surveys the modeling and control approaches to deal with these behaviors. The previous discussions are summarized in this section along with concluding remarks.

A. Modeling

The idea of modeling piezo-actuated stages is to establish effective models for describing their behaviors of hysteresis, creep and vibrational dynamics, which undergos from the static nonlinear modeling period to comprehensive dynamic modeling period. Among the three behaviors, the most difficult problem is to represent the hysteresis with available mathematic models because the hysteresis are both amplitude-dependent and rate-dependent nonlinearity as well as the nonlocal memoryless. The challenge lies in that a hysteresis model should be not only able for precise hysteresis description but also effective for controller design. Therein, the Preisach model is the most popular model in describing the hysteresis in piezoelectric actuators in the literature because of its general structure. However, until now, the inverse of a Preisach model can only be approximately constructed using different numerical methods. In this sense, the P-I hysteresis model and its variations seem to be more competitive due to the existence of the analytical inverse expressions and attract more and more attentions in real-time applications. In fact, the P-I model is by nature a subset of the Preisach model, which may limit the applicability of the P-I model. Of course, if the exact condition for converting the P-I model to the Preisach model can be derived, one can directly construct the analytical inverse of the Preisach model based on the inverse results of the P-I model. Unfortunately, this problem has not be solved until now. On the other hand, rate-dependent hysteresis modeling and inverse construction are also challenging research topics in this field.

B. Control

In nanopositioning applications such as the atomic force microscopy, ultra-fast servo tools and nanorobots, there are increasing requirements on the precision and speed of piezo-actuated stages. Therefore, high-bandwidth control of such systems is emerging. To satisfy these requirements, main control efforts are made to compensate for the hysteresis and vibration. As discussed in Section IV, feedforward-feedback control schemes integrating with the feedforward and feedback control approaches are promising. In these control schemes, the inverse compensations of the hysteresis and vibration models are generally treated as complete compensation, where analysis of the inverse compensation errors is usually missed. Then, feedback control approaches are designed for these ideal compensation systems. However, in practice the inverse construction of hysteresis models and vibration dynamics are generally specific and always generates some compensation errors, which also possesses strong sensitivity to the model parameters. Therefore, the stability analysis of the closed-loop system is a challenging task when considering the inverse compensation errors since it is very difficult, if not impossible, to obtain their analytical expressions. Additionally, active damping control techniques are becoming promising to suppress the vibrational dynamics for high-bandwidth control of piezo-actuated stages, especially in the applications with the atomic force microscopy. In these applications, the charge control with the charge amplifier is generally used to eliminate the hysteresis. However, the charge amplifier has not been widely adopted due to its implementation complexity and cost. To date, the voltage amplifier is still the most popular approach to drive piezoelectric actuators. Therefore, development of the active damping controllers with the hysteresis compensators becomes an interesting topic.

C. Emerging Research Problems

In summary, the emerging research problems on piezo-actuated stages includes: 1) rate-dependent hysteresis modeling and inverse construction; 2) active damping techniques for the vibration dynamics; 3) analysis of the compensation errors with the inverse hysteresis and vibration compensations; 4) stability analysis of the feedforward-feedback control systems.

Additionally, the existing modeling and control approaches are mainly developed for the one-degree-of-freedom piezo-actuated nanopositioning stages. Even for the applications with multi-degree-of-freedom stages, the piezo-actuated stages are simply treated as decoupling of each positioning axis in the controller designs. In fact, dynamic cross-coupling effects among the different positioning axes of the multi-degree-of-freedom stages will deteriorate the stage performance especially during the high-speed operations. Therefore, reduction and compensation of these cross-coupling effects should be well taken into account in the future modeling and control works.

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