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Design of hysteresis-compensating iterative learning control for piezo-positioners: Application to atomic force microscopes ☆

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Abstract

This article addresses hysteresis-caused positioning error in piezo-based systems, such as atomic force microscopes. First, we present the design of an iterative learning control algorithm based on the Preisach hysteresis model. For a given output bound, we determine the algorithm's rate of convergence. Second, we compensate for creep in the piezo system to determine a hysteresis model, and then the parameters of the model are used to find an appropriate value of the iteration gain such that convergence of the control algorithm is guaranteed. Finally, we demonstrate the efficacy of the approach, to achieve high-precision positioning, by applying the control algorithm to an experimental atomic force microscope system. Results show that iterative learning control can achieve substantial reduction of hysteresis-caused error, e.g., the tracking error is reduced to 0.24% of the total displacement range, which is approximately the noise level of the sensor measurement.

Keywords: Piezo-positioner; Hysteresis; Preisach model; Atomic force microscope; Iterative learning control; High-precision positioning

1. Introduction

This article studies the design of an iterative learning control algorithm to correct for hysteresis-caused error in piezo-based positioning systems, for example atomic force microscopes (AFMs). It is noted that relatively long-range, precision positioning of the AFM-probe tip (relative to a sample surface) is critical during AFM operations. For example, during AFM-based nanofabrication, piezos are used to position the AFM-probe tip at a desired location and then a surface feature is created by changing the interaction between the AFM-probe tip and sample surface [1–3]. One common technique for creating surface features is to apply a voltage between the probe tip and sample surface to induce local anodic oxidation, e.g., see [1]; the feature sizes achieved with this technique is smaller than 100 nm [4,5]. In such nanofabrication applications, it is not only necessary to achieve precision in the AFM-probe-tip position to create nanosized features, but it is also necessary to achieve precision positioning over relatively long ranges (tens of microns), e.g., to pattern interconnects between devices and electrical-contact pads [1,5]. Without precise control of the probe-tip misalignment of the interconnects may result, subsequently leading to incomplete electrical connections between the nanosized components. The challenge in using piezos to achieve precision positioning (over long ranges) is hysteresis behavior causes substantial tracking error – as much as 15% of the total displacement range [6,7]. As a result, there is a need to compensate for the hysteresis-caused error in AFM-based nanofabrication. Furthermore, similar positioning-error problems due to hysteresis arise in other AFM-based applications such as high-density data storage [3] and nanometrology [8]. Recently, our research has developed

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and showed convergence of an iterative learning control (ILC) method to compensate for Preisach-type hysteresis effect in piezo-positioners [9]. In this article, we illustrate the design of this ILC method for an experimental AFM system. Our experimental results show that ILC can achieve substantial reduction of hysteresis-caused positioning error, e.g., the tracking error can be reduced to the noise level of the sensor measurement.

Iterative learning control (ILC) [10] is well suited to compensate for hysteresis-caused positioning errors during repetitive AFM operations. For instance, in AFM-based high-density data storage, the probe tip is scanned repetitively back and forth across the sample surface while read/write operations are performed [3]. Such repetitive motion of the AFM-probe tip enables the application of ILC techniques to learn and compensate for the hysteresis-caused errors. It is noted that even when the AFM operation is not repetitive, the ILC method can still be used. For example, the AFM-probe-tip trajectory may not be repetitive during nanofabrication; however, ILC can be used off-line to *learn* the hysteresis-compensating input and then the input can be applied to the piezo-positioner – as a feedforward input – to achieve precision positioning during the nanofabrication process. In contrast to other approaches to find the hysteresis-compensating feedforward input, e.g., model-based approaches as described in Refs. [7,11–13], an advantage of ILC is it is effective even in the absence of accurate models [10,14]. This is particularly important for piezo-systems because the model can change over time, say due to aging effects. Furthermore, as in any feedforward control approach, ILC can be augmented with feedback control for additional improvement in the positioning performance, say to account for external perturbations, or to stabilize the positioning system [15,16]. This method can also be used in conjunction with other approaches to reduce hysteresis in piezos, such as charge control methods [17].

Although the ILC approach is well suited for precision-positioning of piezos in AFM applications, the challenge is to develop convergence criteria needed to design the ILC algorithm. The difficulty in proving convergence of ILC algorithms for hysteretic systems arises due to two reasons: (i) branching effects and (ii) nonlinearity of each branch [18]. The latter issue can be addressed by standard ILC methods. For example, the convergence of ILC on a single branch was shown in [19], in which the hysteresis nonlinearity was modeled as a single branch (using a polynomial). Alternatively, a functional approach was proposed for systems that satisfy the incrementally strictly increasing operator (ISIO) property [20]; however, the branching effect in hysteresis results in loss of the ISIO property [9]. The reason branching causes problems in proving convergence is because branching prevents the ILC algorithm from predicting the direction in which the input needs to be changed based on a measured output error. For example, the input error can grow from one iteration to the next. To illustrate this loss in direction due to branching effects, consider a typical hysteresis (output (v) vs. input (u)) response shown in Fig. 1. Suppose this hysteresis curve corresponds to a desired output v_d and its associated input u_d. Assume at some time t we have a desired output value $v_d(t)$. On the hysteresis curve in Fig. 1 there are two possible inputs associated with $v_d(t)$, one on the ascending branch $\mathcal{B}_a$ and one on the descending $\mathcal{B}_d$. Now for convenience, let the initial input and its corresponding output $(u_0(t), v_0(t))$ be at the origin as shown in Fig. 1. Suppose for the next trial we wish to determine the next input based on the current measured output error. What we discover is in comparison to the current input $(u_0(t))$, the desired input to achieve the desired output $(v_d(t))$ could be either (i) the higher value $(u_H(t))$ on the ascending branch $(\mathcal{B}_a)$; or (ii) the lower value $(u_L(t))$ on the descending branch $(\mathcal{B}_d)$. But unfortunately, the current output error $(v_d(t) - v_0(t))$, which is positive in this example, cannot be used to determine the direction in which the input needs to be changed at the next trial; the input error could be positive $((u_H(t) - u_0(t)) > 0)$ or negative $((u_L(t) - u_0(t)) < 0)$. If, for example, the desired output was on the descending branch $\mathcal{B}_d$, then the positive output error would cause the input for the next trial to move in the positive direction (away from the input $u_L(t)$). Therefore, the input could grow at the next trial. It is noted that ILC relies on the ability to predict the direction in which the input needs to be changed to reduce the output error; therefore, the branching effect makes it challenging to show convergence of ILC for hysteretic systems.

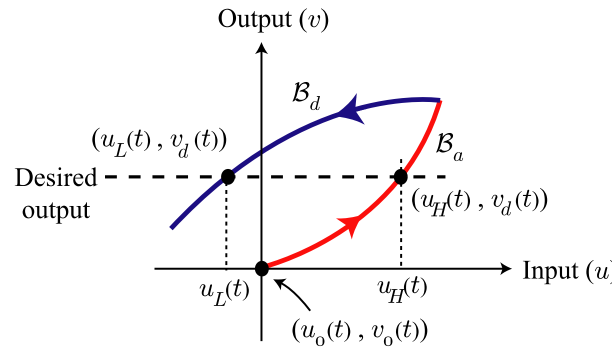

Fig. 1. Hysteresis curve with two branches.

The inability, to predict the direction in which the input needs to be changed for reducing the output error in hysteretic systems, can be overcome if the input–output behavior is restricted to belong on one single branch. For instance, if the input–output behavior belongs on the ascending branch (e.g., $\mathcal{B}_a$ in Fig. 1), then the input should be increased if the output error $(v_d(t) - v_0(t))$ is positive. (*Similarly, the input should be decreased if the output error is negative.*) This observation that the direction can be determined from the output error on a single branch was used to prove the convergence for an ILC algorithm for hysteretic systems in [9]. The work developed convergence criteria for a single branch (desired output trajectories that are monotonic in time) and then proved the convergence of general output trajectories by, first, partitioning a general output trajec-