Identification of coupled hysteresis, creep, electric and vibration dynamics in piezoelectric actuators for high-bandwidth and precision motion control

Lei Liu[1], Kok Kiong Tan[2], Si-Lu Chen[3], Chek Sing Teo[3], Tong Heng Lee[2] ,Wei Lin[3],
[1]University of Singapore, Singapore
[2]Dept. of Electrical and Computer Eng., National University of Singapore, Singapore
[3]Singapore Institute of Manufacturing Technology, Singapore
Corresponding author: wlin@SIMTech.a-star.edu.sg

Abstract

Precision fast motion control of piezoelectric actuators (PAs) is more and more appealing, but the closed loop bandwidth is limited due to the coupled hysteresis, creep, electric and vibration dynamics. Thus, this article presents the accurate identification of PA dynamics at broadband frequencies. The identification strategy is divided into three steps according to the characteristics of PA dynamics under different inputs. At first, the creep dynamics is identified using square wave inputs with periods on the order of hundred seconds. Then, the electric and vibration dynamics are identified using square wave inputs with periods on the order of ten milliseconds. Finally, the special harmonic input and the sampling rule are designed, such that the hysteresis nonlinearity can be identified employing singular value decomposition (SVD) technique while the creep, electric and vibration dynamics are eliminated by their model-inversion.

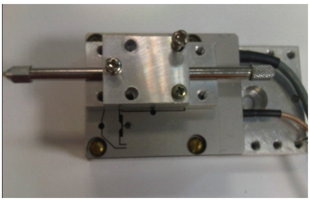
Based on the identified hysteretic dynamics, we design a feedforward-feedback composite controller comprising of a model-based inversion feedforward controller and a PI feedback controller. The feedforward controller is designed to reduce the phase-lag and the magnitude distortion, achieving high-bandwidth motion. Additionally, the simple proportional-integral (PI) controller is employed to guarantee the stability in the presence of disturbances. To demonstrate the identification and compensation strategy, the corresponding experimental studies are performed. High-bandwidth and precision motion is achieved. The RMS tracking error of the reference trajectory at 600Hz (higher than the first resonant frequency of the PA) is less than 1.76% of the trajectory amplitude.

An important advantage of this identification strategy is that it accurately treats the coupling of the static hysteresis and the non-hysteretic dynamics for the purpose of compensating the hystertic dynamics of PAs over a broad range of frequencies. Furthermore, the model-based inversion feedforward can be computed off-line and written into DSP in real-time.

1 Identification of coupled hysteresis, electric and vibration dynamics in Pas

The coupled hysteresis, electric and vibration dynamics is illustrated in Figure 1. H denotes the rate-independent hysteresis, G_{ev} denotes the electric and vibration dynamics, and G_{c} denotes the creep dynamics. u and x are input voltage and output displacement.

(a)



(b)

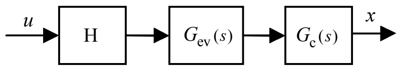


Figure 1: Piezo actuator (a) and its model illustration (b)

The classical Preisach model is employed to represent the rate-independent hysteresis.

$$v = \iint_S \mu(\alpha,\beta)\gamma_{\alpha\beta}[u(t)]d\alpha d\beta,$$

where S is the limiting triangular in Preisach plane and v is the hysteresis output, $\mu(\alpha,\beta)$ is the density function at point (α,β).

The electric/vibration dynamics $G_{\mathrm{ev}}(s)$ and the creep dynamics $G_{\mathrm{c}}(s)$ can be represented as

$$G_{\mathrm{ev}}(s) = k_{\mathrm{ev}} \frac{1}{\tau s+1} \prod_j \frac{\omega_j^2}{s^2 + 2\xi_j \omega_j s + \omega_j^2}, \quad G_{\mathrm{c}}(s) = k_{\mathrm{c}} \prod_i \frac{s+z_{ci}}{s+p_{ci}}$$

where τ is the time constant of the electric dynamics, ξ_j and ω_j are the damping ratio and mode frequency, respectively. The effect of Preisach hysteresis with a square wave input is to alter its magnitude. For a square wave input, the classical

Preisach hysteresis behaves like a nonlinear amplifier without phase delay and dynamic response. This property is already harnessed in the identification of non-hysteretic dynamics.

1.1 Identification of creep dynamics

The identification of creep dynamics is carried out using a square wave input signal with the period of the order of minutes. The accurate period is determined in experiment. Its factor k_c is normalized to 1, since it is absorbed in the hysteretic part. Furthermore, to reduce the measurement noise and the effects due to electric and vibration dynamics, the sampling rate is slower, compared with the sampling used for the electric and vibration components. According to this method, the creep of our PA is identified as

$$\hat{G}_{\mathrm{c}}(s) = \frac{(s+0.01458)(s+0.1716)(s+0.241)(s+1.07)(s+18.29)}{(s+0.01419)(s+0.1684)(s+0.2402)(s+1.053)(s+17.57)}$$

1.2 Identification of electric and vibration dynamics

The identification of the electric and vibration is implemented also using square wave signal, but the period is on the order of seconds. The gain is also set to 1. During this step, the creep effect is eliminated with a model inversion. Furthermore, the sampling rate is as fast as possible to capture the response at high frequencies. The identification result of electric and vibration dynamics is as follows:

$$\hat{G}_{\mathrm{ev}}(s) = \frac{1}{0.0005s+1}\,\frac{2.001\times10^{7}}{s^{2}+6513s+2.001\times10^{7}}\,\frac{5.197\times10^{7}}{s^{2}+785.5s+5.197\times10^{7}}$$

1.3 Identification of rate-independent hysteresis

Harmonic input signals with varying amplitudes are employed to identify the rate-independent hysteresis, since adequate amplitudes, rater than adequare frequencies, are capable to eliminate the persistent excitation condition in the hysteresis identification, Based on SVD, the density function is solved, as shown in Figure 2(a). The identified hysteresis will be validated by the model-based inversion.

2 Model-based compensation of coupled hysteresis, electric and vibration dynamics in PAs

Based on the identified hysteretic dynamics, the model-based inversion feedforward compensator can be constructed as shown in Figure 2(b). It consists of the inverse non-hysteretic dynamics and inverse hysteresis. The reference signal pass through firstly the inverse non-hysteresis dynamics and then the inverse hysteresis.

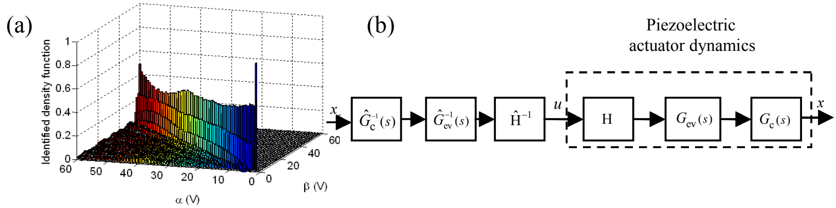


Figure 2: Identified density function of Preisach hysteresis (a) and model–based inversion feedforward (b)

To reject disturbances, a PI feedback controller is also employed. The resulting composite controller gives satisfotory tracking performance at frequencies higher than the resonant frequency. The tracking performance of the trajectoty at 600Hz under the model-based inversion feedforward controller and the composite controller are shown in Figure 3.

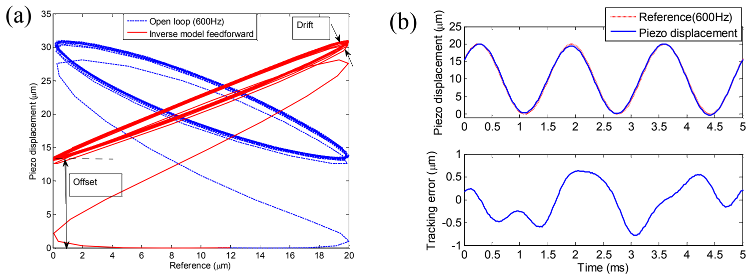


Figure 3: Tracking performance at 600Hz under the feedforwrd controller (a) and the composite controller (b)

References:

[1] S. O. Moheimani, Accurate and fast nanopositioning with piezoelectric tube scanners: emerging trends and future chanllenges, Rev. Sci. Instrum., vol. 79, pp. 071101, 2008.

[2] M. Goldfarb and N. Celanovic, Modeling piezoelectric stack actuators for control of micromanipulation, IEEE Control Systems Magazine, vol. 17, pp. 69-79, 1997.

[3] I. Mayergozy, Mathematical Modeling of Hysteresis and their Application, Amsterdam: Elsevier, 2003.

[4] K. Leang, Q. Zou, S. Devasia, Feedforward control of piezoactuators in atomic force microscope systems, IEEE Control Systems Magzine}, vol. 29, no. 1, pp. 70-82, 2009.