Journal of Process Control 24 (2014) 578–585

Contents lists available at ScienceDirect

Journal of Process Control

journal homepage: www.elsevier.com/locate/jprocont

Piezoelectric-actuated drop-on-demand droplet generator control using adaptive wavelet neural network controller

Hung-Yi Chen*, Jin-Wei Liang

Department of Mechanical Engineering, Ming Chi University of Technology, No. 84, Gungjuan Road, Taishan, New Taipei City 243, Taiwan

ARTICLE INFO

Article history:
Received 18 June 2013
Received in revised form
25 November 2013
Accepted 3 March 2014
Available online 27 March 2014

Keywords:
Drop-on-demand droplet generator
Adaptive wavelet neural network controller
Piezoelectric-actuated system
Dispensing system
Nonlinear hysteresis

ABSTRACT

This paper presents the design, fabrication and control of a piezoelectric-type droplet generator which is applicable for on-line dispensing. Adaptive wavelet neural network (AWNN) control is applied to overcome nonlinear hysteresis inherited in the LPM. The adaptive learning rates are derived based on the Lyapunov stability theorem so that the stability of the closed-loop system can be assured. Unlike open-loop dispensing system, the system proposed can potentially generate droplets with high accuracy. Experimental verifications focusing on regulating control are performed firstly to assure the reliability of the proposed control schemes. Real dispensing is then conducted to validate the feasibility of the piezoelectric-actuated drop-on-demand droplet generator. In order to illustrate the effectiveness of the proposed method, experimental results obtained using the AWNN scheme are compared with their counterparts using traditional PID control. The results indicate that the proposed AWNN scheme not only outperforms PID control but also works well in developing the piezoelectric-actuated drop-on-demand dispensing system. The proposed dispensing system provides droplet chains with an averaged mass as small as 31.5 mg while the associated standard deviation is as low as 0.72%.

1. Introduction

Piezoelectric-actuated systems are often applied in high-precision applications because the systems can provide nanometer accuracy if they are controlled properly. The piezoelectric-actuated system is also known for its fast response, high stiffness. The system, however, exhibits undesired hysteresis behaviors. Such nonlinear hysteretic features lead to problems of severe inaccuracy, instability, and restricted performances when the system is open-loop controlled. Moreover, nonlinear hysteretic characteristics of the piezo-actuated system are difficult to model because the behaviors are not only amplitude but also frequency dependent. Accordingly, existing hysteresis models are either too simple to capture complete hysteretic dynamics or too complicated to be easily implemented in model-based controller design. In addition to nonlinear hysteresis features, offset dead-zone nonlinearity is also observed in the linear piezoelectric motor (LPM) experimental system adopted in this study. Such a nonlinearity appearing in the low control voltage range is caused by static friction and preload. The dead-zone nonlinearity of the system is direction dependent. In other words, magnitude of the static friction in one direction is different from that of the other.

Research effort has been put previously to overcome the nonlinear hysteretic characteristics associated with the LPM-driven or piezoelectric-actuated system. For instance, [1] applied an adaptive wavelet neural network (AWNN) control with hysteresis estimation to improve the control performance of a piezo-positioning mechanism. A new hysteretic model integrating a modified hysteresis friction force function was proposed in [1] to represent the dynamics of the piezo-positioning system. Then, a wavelet neural network (WNN) with accurate approximation capability was employed to approximate the part of the unknown function in the proposed dynamics of the piezo-positioning system. Although the approach proposed in [1] demonstrated improved tracking performances, the method required a complicated hysteresis model. There were other model-based approaches. For instance [2] applied least squares support vector machines (LS-SVM) technique to obtain hysteresis and inverse hysteresis model so that feedforward controller can be implemented. Radial basis function is adopted as kernel function in [2]. The LS-SVM approach adopted in [2] was further extended to an online modeling and compensation approach in [3]. In addition, an online modeling and compensation algorithm based on relevance vector machine was also developed in [3]. Both hysteresis models are capable of updating continuously with subsequent samples. Associated inverse models were constructed so that

* Corresponding author. Tel.: +886 2 29089899x4527; fax: +886 2 29063269.
E-mail address: hychen@mail.mcut.edu.tw (H.-Y. Chen).

http://dx.doi.org/10.1016/j.jprocont.2014.03.003
0959-1524/

feedforward controllers can be effectively implemented. Although the tracking results presented in [2,3] seemed satisfactory, the models and identification methods involved were complicated. Another model-based approach was reported in [4] which proposed a rate-dependent modified Prandtl–Ishlinskii (P–I) operator to account for the hysteresis nonlinearity of a piezoelectric actuator at different actuating frequency. The least-squares fit were performed to identify the weight parameters associated with the modified P–I model. The P–I model is commonly used in the modeling of backlash between gears with one degree of freedom. Although the P–I model could capture the nonlinear hysteresis features well, the method was also complicated. In contrast, [5] chose Bouc–Wen model to describe nonlinear hysteresis behaviors. The particle swarm optimization (PSO) method was adopted to identify the parameters associated with the Bouc–Wen model. Feedforward controller was designed accordingly. Although the hysteresis model used in [5] was slightly simpler the PSO identification algorithm used was complicated.

Unlike the model-based approaches depicted above, [6] investigated a LPM-driven system using a total sliding-mode based genetic algorithm control (TSGAC) and a hybrid resonant inverter. In [6], the linear piezoelectric ceramic motor (LPCM) and its driving circuit were modeled by a nonlinear function with unknown system parameters. Since the dynamic characteristics of the system are highly nonlinear and time varying, direction-based genetic algorithm with the spirit of total sliding-mode control and fuzzy-based evolutionary procedure was applied to attack the problem. The study employed genetic algorithm control as the major controller while the stability of the system was indirectly ensured using the concept of total sliding-mode control without strict constraints and detailed system knowledge. The control scheme applied in [6] was complicated even though tracking performances of the LPCM-driven system illustrated seemed quite satisfactory.

Artificial neural network can approximate a wide range of nonlinear function to any desired accuracy under certain circumstances. This property has been shown in the literatures [7–12]. Among many neural network designs, wavelet neural network control (WNN) attracts much attention in research community because the approach integrates wavelet decomposition property with learning capability of neural network [13–16]. Since WNN can provide at least the same order of approximation accuracy as traditional neural network, they are alternatives in handling tracking control problems. An intelligent control scheme based on WNN is adopted in this study to overcome nonlinear properties of the piezoelectric-actuated system. The adaptive learning rates are derived based on the Lyapunov stability theorem to guarantee the stability of the closed-loop system. The resultant control scheme is denoted as adaptive wavelet neural networks (AWNN) control. A similar adaptive WNN-based approach had been adopted to control a static var compensator (SVC) located at center of the transmission line [16]. AWNN stability analysis in the closed-loop system was performed in [16]. To that end, only brief summary regarding stability analysis will be included in this paper. The WNN seems to be a static model if only a static relation between its inputs and outputs is established and all signals flow in a forward direction. The approach, however, becomes dynamic when feedback signal is adopted as the input to the WNN. Such a configuration is taken in this study. The control task here is to minimize an objective function which is essentially a sum of the squares of control error. The control error on the other hand measures the difference between the reference input and real control output. Therefore, time-varying control output is continuously fed to the WNN algorithm not only as an input but also a feedback signal. System uncertainty and time-varying characteristics can thus be captured in this configuration. In contrast, dynamic wavelet neural networks approach was reported in the literatures [17–21]. Signals in such a network configuration can flow not only in the forward direction but also can propagate backwards, in a feedback sense, from the output to the input nodes. Dynamic wavelet NN with internal states used to model highly uncertain dynamics was reported in [21] and successfully applied to model wastewater treatment process for model predictive control purposes. In this study, the proposed control scheme is tested by using regulation task firstly. After examining the reliability of the proposed scheme, the method is further applied to develop a drop-on-demand droplet generation system.

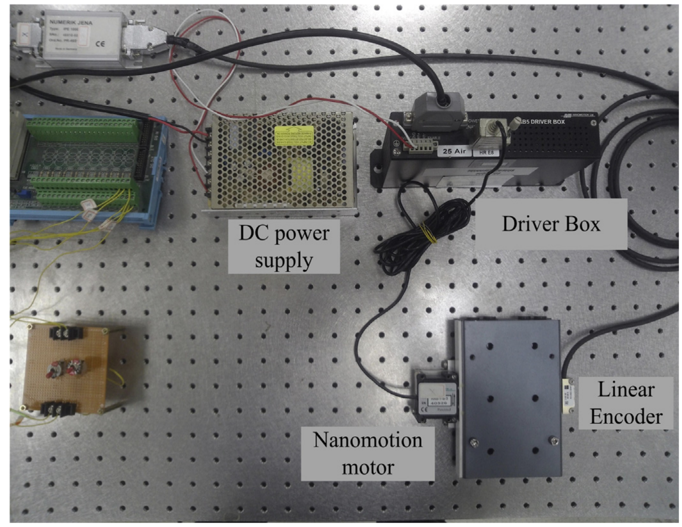

Fig. 1. The LPM-actuated table system.

2. The LPM-actuated table system

A linear piezoelectric motor (LPM) actuated table system consisting of a linear piezoelectric motor (HR8) with its driving unit and a linear encoder with signal conditioning unit (PCL-833) is shown in Fig. 1. In addition, Fig. 2 presents a schematic diagram of the experimental set-up. According to Fig. 2, in order to control the piezoelectric system, a PC-based control unit is implemented in which the control voltage is calculated and converted to analog signal by using a D/A interface card (PCI-1716). The control was implemented in a PC unit using "Turbo C" coding. The calculated control signal is sent to piezoelectric actuator driver unit to actuate the HR8 LPM. Note that a linear relationship exists between the piezoelectric actuator velocity and the driver control voltage. Therefore, the actuator and driver can be modeled as a DC motor with internal friction. Displacement measurement obtained from linear encoder is adopted as the feedback signal to accomplish the closed-loop control. The resolution of the linear encoder is 0.1 μm. Moreover, an input limiter was selected to avoid damage occurred to the PC. The sampling rate was chosen as 500 Hz during experimental investigation course.

3. Adaptive wavelet neural network (AWNN) controller design

3.1. Wavelet neural network (WNN)

Fig. 3 shows the intelligent control block daigram proposed for the precise positioning of the LPM-actuated table system. As seen in Fig. 3, the intelligent control system includes an online training algorithm, adaptive learning rates derived from Lyapunov stability criterion and the wavelet neural network controller. According to the control block diagram, the output of the intelligent control system u is used to drive the LPM. The latter in turn drives the table