Nanopositioning Fuzzy Control for Piezoelectric Actuators

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Abstract— This paper aims to design a fuzzy controller to manipulate piezoelectric (PZT) actuators for nanopositioning applications. A Bouc-Wen model is adopted to represent the dynamics and hysteresis behavior in a piezo-actuated positioning stage. A simulation work is carried out for fuzzy control development and the results are compared to that obtained using PI controller based on observer. The results affirmed the potential of the developed fuzzy control algorithm whereas the tracking error is reduced to a sub-nanometer precision.

Index Term— Actuators, Fuzzy control, Nanotechnology, Position control.

I. INTRODUCTION

Recent advances in precision engineering and the concurrent development of advanced manufacturing techniques have the result that machined and manufactured components are no longer restricted to micrometer scale, but can now be fabricated at nanometer scale. The advanced technologies have given rise to an urgent requirement for the development of precise positioning systems capable of executing displacements with nano scale resolution. So, the nanopositioning has become an important developing target for meeting the requirements of the semiconductor, optical communication, biomedical applications, precise industrial applications, …etc [1].

Piezoelectric actuators are chosen to design precise positioning systems for achieving the sub-mic or nanopositioning applications such as scanning tunnelling microscopy, biomedical equipments, nano robots, automotive industry, …etc [2-3]. The most commonly produced piezoelectric ceramics are lead-zirconate-titanate (PZT). Piezoelectric material is used to convert electrical energy to mechanical energy and vice-versa. Piezoelectric sensors are used in a variety of applications to convert mechanical energy to electrical energy such as: pressure-sensing applications, detecting imbalances of rotating machine parts, ultrasonic level measurement, flow rate measurement, sound transmitters (buzzers), sound receivers (microphones), …etc. However, piezoelectric actuators convert electrical energy to mechanical energy, and are used in many applications such as: scanning microscopy, patch clamp, gene manipulation, vibration cancellation, R/W head testing, hydraulic valves, drilling equipment, …etc. PZT actuators have many advantages such as [2]-[5]:

- Piezoelectric actuators have excellent resolution in displacement, high stiffness, high electrical mechanical coupling efficiency, small size, small heat expansion, low power consumption and fast response.
- The piezoelectric actuators make motion in micrometer range with sub-nanometer precision.
- There are no moving parts in contact with each other to limit the resolution.
- The piezoelectric actuators capable of moving loads of several tons and cover travel ranges of several (100 µm) with resolutions in the sub-nanometer range [2].
- The piezoelectric actuators behave pure capacitive load, so they consume virtually no power.
- The piezoelectric actuators do not produce magnetic field nor are they affected by them.

However, the piezoelectric actuators have the disadvantage of hysteresis, resonant frequency and creep behaviors, which severely limit system performance such as giving rise to undesirable inaccuracy or oscillations, even leading to instability [6], [7]. Therefore, appropriate closed-loop control methodologies have been established to achieve the desired positioning accuracy of the piezoelectric actuation systems. Recent applications include a combination of a feed-forward model in a feedback control with an input shaper [8], a tracking control of a piezoelectric actuator with feed-forward hysteresis compensation [9]-[10], PI control with inverse model compensation [11], sliding-mode control [12], and fuzzy control methodology [13]. However, Ofri et al. used a control strategy based on fuzzy logic theory for vibration damping of a large flexible space structure controlled by bonded piezoceramic actuators [14], as fuzzy controllers are most suitable for systems that cannot be precisely described by mathematical formulations [13].

This paper is organized as follows. Section I presents the literature work and research motivations in nanopositioning control using PZT actuators. Section II describes the dynamic model for PZT actuated positioning stage. The developed control algorithms: PI based observer as developed in the literature and the proposed fuzzy controller are introduced in Section III. Simulation results are presented and discussed in Section IV. Finally, conclusion is drawn in Section V.
II. DYNAMIC MODEL OF PZT ACTUATED POSITIONING STAGE
The piezo-actuated positioning stage is described in [15]. It consists of two parts: positioning mechanism and a piezoelectric actuator. The dynamic model is identified experimentally using the time response method that is applied to find the natural frequency and the damping ratio using an impact hammer (Kistler, 9722A500), a laser positioning sensor (National, LM300 ANL3531C2), and a dynamic signal analyzer (Addlink: siglab 20–42). The testing structure is shown in Fig. 1.

![Piezo-actuated positioning stage](image)

Fig. 1. Piezo-actuated positioning stage [16]

The positioning mechanism is equivalent to a second order (mass-spring-damper) mechanical system; while the PZT actuator is a force generator as shown in Fig. 2.

![Dynamic model of piezo-actuated stage](image)

Fig. 2. Dynamic model of the piezo-actuated stage [15]

The dynamic equation for the above system can be written as [2], [15], [16]:

$$m\ddot{x} + b\dot{x} + kx = f = d k v$$  \hspace{1cm} (1)

Where:
- \(m\): The effective mass of actuator,
- \(b\): The damping coefficient,
- \(k\): The stiffness,
- \(f\): The generated force from applied voltage,
- \(v\): The applied voltage on PZT actuator,
- \(d\): The ratio between the displacement and applied voltage.

The hysteresis is observed in the open-loop operation when the driving voltage is applied in a reverse direction. It depends on crystalline polarization effects, and it increases with increasing the applied voltage. The relation between the displacement and applied voltage is nonlinear, and can be determined by hysteresis model given in [7]. In the literature, there are many approaches to describe the hysteresis nonlinearity: Low and Gao [17], Michael and Nikola [18], Mayergoyz [19], and Bouc-Wen model [15].

The Bouc-Wen model is a nonlinear and not analytic; it is applied to describe the nonlinearity of positioning mechanism and a piezoelectric actuator as follows [15]:

$$\dot{\mathbf{h}} = a_{1} \dot{\mathbf{v}} - \beta_{1} [\dot{\mathbf{h}} | \mathbf{h}] + \gamma_{1} |\mathbf{h}| \dot{\mathbf{h}}$$  \hspace{1cm} (2)

$$h = a_{2} \dot{\mathbf{v}} - \beta_{2} [\dot{\mathbf{h}} | \mathbf{h}] + \gamma_{2} |\mathbf{h}| \dot{\mathbf{h}}$$  \hspace{1cm} (3)

Where:
- \(h\): Represents the hysteresis equation,
- \(x\): The displacement of the stage,
- \(\dot{x}\) and \(\ddot{x}\) are the derivatives of \(x\) and \(h\) with respect to time \(t\),
- \(v\): The applied voltage,
- \(\mathbf{p}\): The initial displacement as \(v = 0\),
- \(a_{1}, \beta_{1}\), and \(\gamma_{1}\) are the parameters used to determine the hysteretic loop.

The identified parameters are given in Table I [15].

<table>
<thead>
<tr>
<th>Table I: Estimated parameters for Bouc-Wen model</th>
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<tr>
<td>(M)</td>
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The above parameters are used in the simulation work (section IV).

III. CONTROL STRATEGIES
The hysteresis is a non-linear mapping with local memory. It causes positioning errors and limits the operating speed in PZT actuators [16]. Therefore, closed-loop control is necessary to overcome this problem. In this paper, two control approaches are developed to compare between them:
- PI controller based observer
- Fuzzy control

A. PI controller based observer
The feed-forward controller is used to determine the inverse hysteresis between the applied voltage and the displacement. As the hysteresis \(h\) in equations (2), (3) cannot be measured by a sensor, so a hysteresis observer is used to estimate its effect on PZT. For linear systems, the Luenberger observer has advantages in that its structure is simple and it is easy to implement. However, the modeling of equations (2), (3) is nonlinear, so the Luenberger observer has to be modified to satisfy this nonlinear model as given in [15], [20]-[21]. A feedback PI controller with observer is used to estimate \(h\) as shown in Fig. 3.
controller where the output is the incremental change of the control signal as a function of error signal and its rate of change. The former can be used for type one dynamic processes that have a self-integrating action due to a pole at the origin to cancel the steady state error; while the later is preferable to be used if the process is type zero where the controller involves the integral action. In our application; the piezo-actuated stage is type zero process. So, the integral action is added in developing fuzzy controller like PI action. Fuzzy controller consists of the following functional blocks [23]-[25]:

**Fuzzification**

The fuzzy control initially converts the crisp error and its rate of change in displacement into fuzzy variables; then they are mapped into linguistic labels. In practice; the rate of change of output is fuzzified instead the rate of change of error to avoid the jump in derivative action at the instant of step change of the reference input. Membership functions are defined within the normalized range [-1,1], and associated with each label: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). Membership functions for the inputs (error and change of displacement) and output (volt) are similar as shown in Fig. 5.

**Rule Base**

The mapping of the fuzzy inputs into the required output is derived with the help of a rule base. Each rule of the fuzzy control is characterized with an IF part, called the antecedent, and with a THEN part called the consequent. The antecedent of a rule contains a set of conditions and the consequent contains a conclusion. However, the inference strategy is the Mamdani algorithm with seven membership functions for each input, so the if-then rules are forty nine rules.

**Defuzzification**

The controller output is a fuzzy in nature and has to be converted into a crisp value by using one of the common defuzzification techniques. In this paper; the Center Of Area (COA) is used as a defuzzification method.

**IV. SIMULATION WORK**

The simulation work is carried out using Matlab/Simulink simulation environment. The sampling time is selected as 0.1 msec whereas the PZT has a fast dynamic response. A simulink model is carried out to realize equations (2), (3) using parameters in Table I. The open-loop response of PZT actuated positioning stage is shown in Fig. 6. A sequence of
up and down voltage as building signal (stair case) is applied to the model with steps of [20, 40, 60, 80, and 100]. Fig. (6.b) shows hysteresis nonlinearity in the displacement of PZT actuator. The output also has a resonant frequency at the step change of the reference input.

![Image](https://example.com/image1)

**Fig. 6.** Open loop response

The closed loop simulation results for PI control based on observer are shown in Fig. (7.a). The hysteresis is significantly reduced due to the predication of its effect using observer and the controller compensates its effect using a feed-forward action. The output displacement tracks perfectly the reference signal using PI control action. However, this response includes a transient resonant mode when the reference signal is changed suddenly and it has also a small delay to track the reference signal.

Fig. (8.a) shows the output response for piezoelectric actuator using fuzzy controller. The hysteresis is reduced and the relation between the applied voltage and the displacement is almost linear as shown in Fig. (8.b). The steady state tracking error using PI control was 20 nm; while in the case of fuzzy control it is reduced to less than 0.02 nm which gives a highly precision in positioning applications.

The output displacement of fuzzy controller tracks the reference input faster than PI control. The response is more damped and resonant mode is eliminated. The control signal in both cases is shown in Fig. 9.

![Image](https://example.com/image2)

**Fig. 7.** Closed loop response using PI base observer

![Image](https://example.com/image3)

**Fig. 8.** Closed loop response using Fuzzy control
The energy consumed for the PI controller is computed as 7.3 KW; while the fuzzy controller is slightly increased to 7.5 KW. It is observed that the fuzzy controller has a smooth action rather than PI controller.

V. CONCLUSION

The Bouc-Wen model of piezoelectric actuator has been adopted in simulation work to represent a real time model of a piezo actuated positioning stage. Two different controllers are applied to treat the hysteresis in PZT actuators. At the level of energy consumption, the two algorithms are relatively comparable. The fuzzy control gives a faster response, over damped transient response and a smooth control action.

The PI controller has a limited performance as the model is nonlinear. A superior performance is obtained using the developed fuzzy algorithm; whereas the tracking error is reduced to a sub nanometer precision.

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REFERENCES