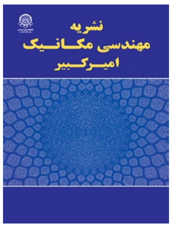

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Control of a Piezoelectric Nano-Actuator based on Flexoelectric Size-Dependent Theory

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ABSTRACT: In this paper, for the first time feedback control algorithms and fuzzy control are implemented for tip tracking control of a piezoelectric size-dependent cantilever nanobeam as a nano-actuator to a desired path. The governing partial differential equation of motion is obtained based on a size-dependent high-order flexoelectric theory. The equations of motion for an isotropic piezoelectric Euler-Bernoulli nanobeam are derived based on the von-Karman geometric nonlinearity besides employing the Hamilton's principle and variational approach. In order to reduce the governing partial differential equations into a set of ordinary differential equations the Galerkin projection method is implemented. By introducing a new set of variables, the state space model of nanobeam is derived. The state feedback, integral state feedback and fuzzy control algorithms are employed to achieve a desired output for tip tracking. Regarding to the findings of this paper, it can be concluded that the fuzzy controller, integral state feedback and state feedback controller have the best performance in that order.

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1- Introduction

In nano scale, the dielectric polarization depends not only on the strain tensor but also on the curvature tensor. Hence, it can be deduced that the flexoelectric effect is universally present in all nano scale dielectrics [1]. Tadi [2] attempted to derive piezoelectric nanobeam formulation in the general case by using the size-dependent piezoelectricity theory. Mechanical vibrating elements are used in a large number of NanoElectroMechanical Systems (NEMS), for sensing and actuating. In these systems, it is important to achieve a high sensitivity. So far the most focused control topic has been the stabilization of NEMS resonators. It can be seen that, although in recent years, several studies have developed the dynamic modeling and vibration analysis of nonclassical nanobeams however tracking control of the Piezoelectric Nanobeams (PNb) with the flexoelectric effects has not been considered yet. Hence, vibration of a PNb is formulated based on the nonclassical continuum mechanics. The governing equations and boundary conditions are derived using the Hamilton's principle. The Galerkin method is employed to discretize the governing partial differential equations. Tip tracking control algorithms for piezoelectric nanocantilever beam are developed, and the simulation results are presented and compared for the three proposed methods.

2- Nonclassical Piezoelectricity Model

Based on size-dependent piezoelectricity, the strain energy of piezoelectric isotropic elastic materials with infinitesimal deformations occupying volume $\mathcal{V}$ is expressed as [1]:

$$U=\frac{1}{2}\int_{v}\left(\sigma_{ji}e_{ij}+\mu_{ji}k_{ij}-D_iE_i\right)dv \tag{1}$$

where $\sigma_{ji}, e_{ij}, \mu_{ji}$ and κ_{ij} represent the components of the classical stress tensor, deformation strain tensor, couple-stress tensor, and curvature tensor, respectively [1]. D_i and E_i stand for electric displacement vector and the electric field, respectively [1]. The electric field and potential relationship is expressed by $E_i=-\Phi_{,i}$ [3].

Employing the Hamilton's principle beside neglecting the axial inertia i.e. $\frac{\partial^2 u}{\partial t^2}=0$ and the terms due to rotary inertia effects, i.e. $\frac{\partial^3 y}{\partial^2 t\partial x}=0$ and $\frac{\partial^4 y}{\partial x^2\partial t^2}=0$, and supposing the dielectric charge density in the volume as $\rho_e=0$, the equations of motion and the corresponding boundary conditions are obtained as:

$$\delta u:\quad EA\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial x}+\frac{1}{2}\left(\frac{\partial y}{\partial x}\right)^2\right)=0$$
$$\text{and}\quad \delta u\left[EA\left(\frac{\partial u}{\partial x}+\frac{1}{2}\left(\frac{\partial y}{\partial x}\right)^2\right)\right]_0^L=0 \tag{2}$$

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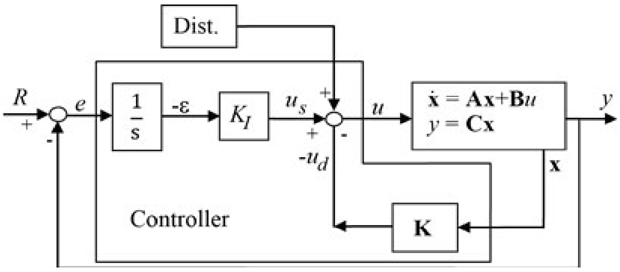

Fig. 1. Integral state feedback control system

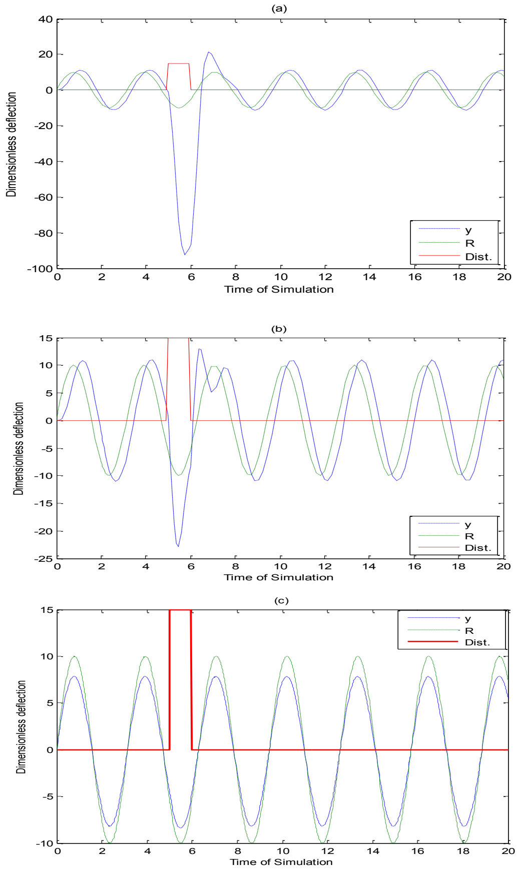

Fig. 2. Tip tracking of the PNb a) the state feedback control, b) the integral state feedback control and c) the Mamdani fuzzy control.

$$\delta y:\ \left(EI+4\mu l^2A\right)\frac{\partial^4 y}{\partial x^4}-EA\frac{\partial}{\partial x}\left(\left(\frac{\partial u}{\partial x}+\frac{1}{2}\left(\frac{\partial y}{\partial x}\right)^2\right)\frac{\partial y}{\partial x}\right)-2\frac{\partial^2 E_{11}}{\partial x^2}+F_{11}\frac{\partial^2 y}{\partial t^2}=0 \quad (3)$$

$$\text{and } \delta y\left[\left(EI+4\mu l^2A\right)\frac{\partial^3 y}{\partial x^3}-EA\left(\left(\frac{\partial u}{\partial x}+\frac{1}{2}\left(\frac{\partial y}{\partial x}\right)^2\right)\frac{\partial y}{\partial x}\right)-2\frac{\partial E_{11}}{\partial x}\right]_0^L=0$$

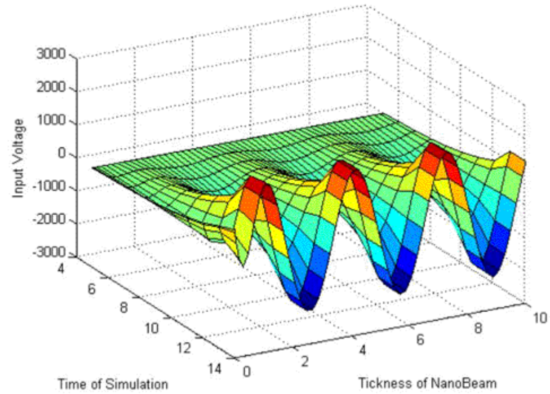

Fig. 3. Input voltage versus the PNb thickness

$$\delta\Phi:\quad \varepsilon\left(\frac{\partial^2\Phi}{\partial x^2}+\frac{\partial^2\Phi}{\partial z^2}\right)+2\frac{\partial f}{\partial z}\left(\frac{\partial^2 y}{\partial x^2}\right)=\rho_e \text{ and}$$

$$\delta\Phi\left[\int_A\left[\varepsilon\frac{\partial\Phi}{\partial z}+2f\left(\frac{\partial^2 y}{\partial x^2}\right)\right]dA\right]_{-\frac{h}{2}}^{\frac{h}{2}}=0 \text{ and} \quad (4)$$

$$\delta\Phi\left[\int_A \varepsilon\left(\frac{\partial\Phi}{\partial x}\right) A=0\right]_0^L=0$$

$$\delta\left(\frac{\partial y}{\partial x}\right):\quad \delta\left(\frac{\partial y}{\partial x}\right)\left[\left(EI+4\mu l^2A\right)\frac{\partial^2 y}{\partial x^2}-2E_{11}\right]_0^L=0 \quad (5)$$

where $E_{11}=\int_{\frac{-b}{2}}^{\frac{b}{2}}\int_{\frac{-h}{2}}^{\frac{h}{2}} f\left(\frac{\partial\Phi}{\partial z}\right)dydz$ and $F_{11}=\int_{\frac{-b}{2}}^{\frac{b}{2}}\int_{\frac{-h}{2}}^{\frac{h}{2}}\rho dydz$.

Considering the reverse effect of a PNb, the electric potential field is assumed as $\phi(x,z,t)=\cos(\beta z)\hat{\phi}(x,t)+\frac{V_0(t)}{h}z$ [4].

The finite dimensional dynamic system will be derived through the conventional procedure of the Galerkin method beside considering the lateral deflection as $y(x,t)=\sum_{i=1}^{n}q_i(t)\phi_i(x)$:

$$M\ddot{q}(t)+kq(t)=BV_0(t) \quad (6)$$

where $\hat{M}_{ij}=\int_0^1\phi_i\phi_j dx$, $\hat{K}_{ij}=\left(1+\frac{4\mu l^2A}{EI}\right)\int_0^1\phi_i''\phi_j''dx$ and $\hat{B}_j=\left(\frac{2bL^2 f}{EIh}\right)\phi_j'(1)$

3- Tip Tracking Control

The control objective is to drive the deflection of the tip point of the PNb to a desired oscillation. For the control design purpose, it is convenient to rewrite the Ordinary Differential Equation (ODE), i.e. Eq. (6), into a state space model.

3- 1- State feedback control

The goal is to affect the system specifically to show a desired behavior tracking at tip point. For tip tracking, two state feedback controllers are designed (state feedback control and integral state feedback control). Uncertainties in the plant model parameters or disturbances acting on the plant may create steady-state control errors. In order to solve this problem, one can use an integral state feedback control (Fig. 1).

3- 2- Fuzzy controller design

For a proportional fuzzy controller with the control error $e(t)=R(t)-y(t)$ and differentiation of error with respect to the time t i.e. $(\dot{e})$ as an input, with the variable $u(t)$ as the output, one can obtain the rule base as:

IF $\mathrm{e}=\mathrm{P}$ and $\dot{\mathrm{e}}=\mathrm{P}$ THEN $\mathrm{u}=\mathrm{VLP}$ and so on.

4- Results and Discussion

In this section, to verify the effectiveness of the proposed control algorithms, for a PNb made of $BaTiO_3$ numerical simulations are carried out. The lateral tip tracking of the PNb for a sinusoidal wave reference input with the pulse noise at time 5 are depicted in Fig. 2.

As it can be seen the lateral tip tracking can be achieved. Also, it can be inferred that, the state feedback control is not a good robust controller as we expected, whereas the best controller is a fuzzy one. The effect of the beam thickness on the input voltage during the tracking time can be seen in Fig. 3. It can be deduced that by decreasing the nanobeam thickness, the input voltage decreases significantly.

5- Conclusions

The tip tracking of the reverse piezoelectric effect on the PNb based on size-dependent flexoelectric, was investigated. Hamilton's principle was employed to derive the governing equations on the basis of the Euler-Bernoulli beam theory. The Galerkin method was implemented to discretize the equations of motion for the control design purposes. Three different controllers, the fuzzy controller, the integral state feedback and the state feedback controller, were analyzed. Regarding the executed analysis and simulation, it was demonstrated that the fuzzy controller is the best one. It was also discussed that to achieve the tracking in the presence of a noise, system needs a very large supply input voltage. This raised issue can have several different solutions, such as, decreasing nanobeam thickness as it was illustrated by simulation.

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