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Research article

Suppression of the noise-induced effects in an electrostatic micro-plate using an adaptive back-stepping sliding mode control

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A B S T R A C T

In this work, an adaptive backstepping sliding mode control approach is applied through the piezoelectric layer in order to control and to stabilize an electrostatic micro-plate. The mathematical model of the system by taking into account the small fluctuations in the gap considered as bounded noise is carried out. The accuracy of the proposed modal equation is proven using the method of lines. By using both approaches, the effects of noise are presented. It is found that they lead to pull-in instability as well as to random chaos. A suitable backstepping approach to improve the tracking performance is integrated to the adaptive sliding mode control in order to eliminate chattering phenomena and reinforce the robustness of the system in presence of uncertainties and external random disturbances. It is proved that all the variables of the closed-loop system are bounded and the system can follow the given reference signals as close as possible. Numerical simulations are provided to show the effectiveness of proposed controller.

1. Introduction

Electrostatic actuators are commonly used in many applications such as relays, grippers, pressure sensors, pumps, valves, optical switches, micro-mirrors and micro-motors [1]. However, this actuation type is prone to highly nonlinear dynamics, which leads to pull-in instability and can affect highly the electrostatic actuators. Besides, the presence of the temperature variation [2], squeeze films [3], fluids loading [4], mechanical shock [5], noise effects [6], parasitic [7], fringing fields effects and intermolecular forces [8] affects considerably the dynamics, the pull-in instability and contribute to limit the performance or to the deterioration of these actuators.

In order to enhance the performance and the stability of electrostatic devices, several researchers have been interested by the analysis and control of the effects of geometric and electrostatic nonlinearities by driving the system parameters. Thus, many control approaches have been developed for electrostatic devices in particular [7–11] and for nonlinear systems in general [12–15]. To improve the tracking performance for nonlinear systems with full-state constraints, some authors proposed to combine the backstepping barrier lyapunov function with neural networks control scheme [16] and Nussbaum gain technique [17]. A shortcoming of these proposed control techniques is that, the authors did not consider the robustness of controller. In order to solve this problem in the case of electrostatic actuator with output constrained and uncertain time delay, Luo and Song [18] proposed to combine an adaptive neural-network-based backstepping scheme with barrier lyapunov function and tracking differentiator in controller design to analyze nonlinear dynamics and chaotic behavior. Note that the aforementioned works limited their works to consider parametric uncertainties without consider external disturbances. Due to that, Vagia [8] enhanced backstepping controller with an adaptive dynamic surface technique and an H_∞ control scheme in order to take into account the parametric uncertainties and periodic external disturbances. However, it is well known that, when micro-resonators operate, small fluctuations in the gap such as Brownian motion, thermal mechanical noise and random vibration will cause frequency fluctuations [6,19]. Note that in all the aforementioned works concerning the stabilization and the control of electrostatic micro-actuators, the small fluctuations in the gap considered here as a stochastic process have not been explicitly taken into account in the controller design. However, stochastic processes are inevitable in practical applications [20]. Due to this fact, many researchers have been actively interested in this topic and many control strategies have been proposed [20–25].

The sliding mode control strategy is a systematic approach to retaining asymptotic stability and robust performance with time

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varying properties, uncertainties, nonlinearities and various external disturbances. However, the use of this controller can cause the chattering phenomenon due to the presence of the discontinuous function and affect the performance of this controller. Moreover, the backstepping procedure is a systematic design technique for globally stable and asymptotically adaptive tracking controllers for a class of nonlinear systems such as the strict feedback nonlinear systems. To obtain satisfying performances of control algorithms (i.e. applicable to more systems [26] with the reduction and elimination of chattering phenomenon [27]), many researchers have considered the adaptive sliding mode control, based on the backstepping design methodology and its application in various actual engineering systems such as static var compensator [28], flexible spacecraft [29], MEMS vibratory gyroscope [27] and mobile manipulator [30]. Moreover, in the last decade, in order to control stochastic process in actual engineering systems, many control algorithms based on backstepping control techniques [31–33] have been proposed with success. However, the adaptive backstepping sliding mode scheme has not previously been developed in order to control the instabilities or stochastic processes and to enhance the performance of the electrostatic micro-plate.

Concerning the modeling, it is well known that electrostatic MEMS are modeled as continuum and deformable structures. However, with the presence of electrostatic nonlinearity in the partial differential equation, it is more difficult to approach analytically the solution with and without a control scheme. Due to that fact, most of the works on the control of electrostatic micro-plate used simplified models in which micro-actuators (beams, plates etc…) are assumed as a lumped models and rigid structures [2,34]. An interesting full approach is thus to consider these micro-actuators as deformable structures and to provide a good approximation in order to make possible the analytical approaches. In this work, we use the piezoelectric materials to convert the voltage control into mechanical force in order to track a desired deflection in electrostatic MEMS. But the use of piezoelectric actuators leads to highly nonlinear (hysteresis and creep effects) relationship between the applied voltage and the output displacement [35–38], which affects their precision. However, in the case of a close-loop control strategy, only the hysteresis effect occurs [35–38]. Many researchers have been interested by the development of feedback control strategies without the inverse hysteresis construction [35,37–40] and they have demonstrated that the robust adaptive control is a better approach [38].

Motivated by the aforementioned works and the broad applications of electrostatic MEMS, the aim of the present work is to control and to stabilize an electrostatic micro-deformable plate by taking the small fluctuations in the gap as bounded noises and uncertainties and by using an adaptive backstepping sliding mode controller through a piezoelectric layer. The advantage to use the proposed controller is that, the backstepping control technique adjusts the control system to attenuate the tracking error and the sliding mode control component is used to suppress the bounded disturbances. Moreover, in practical application, it is difficult to obtain the bound of uncertainties and the random disturbances parameters in advance. Due to this difficulty, a simple adaptive algorithm is developed to estimate the bound of uncertainties and the random disturbances parameters. Compared with the existing literature, the contribution of this control scheme can be summarized as follows.

1) The proposed control approach can solve the problems of small fluctuations in the gap of electrostatic micro-plate taken as bounded noise. Although many others actual engineering systems [27–30] also used the same control design. However, the controlled systems in [27–30] have not considered explicitly the presence of stochastic processes.
2) The proposed controller can be developed to provide a good tracking performance and robustness of the controller in real-time of electrostatic MEMS in the presence of parameters uncertainties and disturbances without requiring the knowledge of bounds of uncertainties, noise intensity and amplitude of external random disturbances. Moreover, the proposed control scheme solves the problem of chattering phenomenon in robust sliding mode control design.

The present work is organized as follows: the modeling of the electrostatic micro-plate with random disturbance and the effects of the random disturbance are presented in Section 2. In Section 3, the modal equation is carried out and the finite difference numerical scheme and noise-induced effects using both approaches are presented. The design of adaptive backstepping sliding mode controller is proposed in Section 4. Numerical simulations are given in order to verify the effectiveness of the proposed controller in Section 5. Section 6 gives the conclusion.

2. Modeling of the electrostatic micro-plate

2.1. Physical system

The device considered consists of a two parallel rectangular plates as shown in Fig. 1.

The upper plate is a thin elastic deformable rectangular micro-plate with density $\rho\left(\mathrm{Kg/m^3}\right)$, thickness $h(\mathrm{m})$, damping coefficient $\lambda\left(\mathrm{Ns/m^2}\right)$, length $a(\mathrm{m})$, width $b(\mathrm{m})$, Poisson's ratio ν_s and Young's modulus $Y_s\left(\mathrm{N/m^2}\right)$ and the lower plate is considered as a fixed ground plane.

The deformable micro-plate is perfectly bounded on its upper surface by a piezoelectric layer. This piezoelectric layer has a thickness $h_1(\mathrm{m})$ and a density $\rho_1\left(\mathrm{Kg/m^3}\right)$.

The micro-plate is initially submitted to axial load $P_0(\mathrm{N/m})$ (induced by axial stresses, residual stresses and effect of mid-plane stretching). The governing equation of micro-plate subjected to electrostatic force is obtained using the classical Kirchhoff thin plate theory. This theory is adequate when the thickness-to-length ratio is small to avoid size-dependent effect. However, it is well known that when the axial load (P_0) acts in the middle plane of the membrane forces arise and an additional resultant transverse load. Consequently, the nonlinear differential equation of the plate can be written as below [41]:

$$\rho h\frac{\partial^2 w}{\partial t^2}+\lambda\frac{\partial w}{\partial t}+\left(\frac{\partial^2 M_x}{\partial x^2}-2\frac{\partial^2 M_{xy}}{\partial x\partial y}+\frac{\partial^2 M_y}{\partial y^2}\right)-N_x\frac{\partial^2 w}{\partial x^2}+2N_{xy}\frac{\partial^2 w}{\partial x\partial y}-N_y\frac{\partial^2 w}{\partial y^2}$$
$$=F_{el}(w)+f(t) \tag{1}$$

where $w(x,y,t)$ is the transverse deflection of the micro-plate in meter; M_x and M_y are the bending moments parallel to the x and y

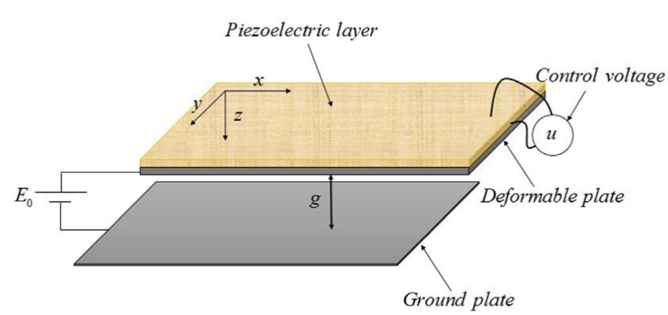

Fig. 1. Electrostatic micro-plate.

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