Control Strategies for Increased Reliability in MEM Comb Drives

AHMET KUZU
Mechatronics Engineering
TUBITAK-MAM-BTE
PK21 41470 Gebze/Kocaeli
TURKEY
ahmet.kuzu@bte.mam.gov.tr

SETA BOGOSYAN (corresponding author)
Dept. of Electrical & Computer Eng.
Fairbanks, Alaska 99775
University of Alaska Fairbanks
USA
s.bogosyan@uaf.edu

METIN GOKASAN
Electrical & Electronics Eng. Faculty
Istanbul Technical University
Maslak 34469, Istanbul,
TURKEY
gokasan@itu.edu.tr

Abstract: - In this study, a chattering free sliding mode controller (SMC) is designed for the control of MEM comb drives. Due to the highly nonlinear structure of the electrostatic comb drive, a robust nonlinear control approach is demonstrated to be more suitable for the control of such systems over linear control methods, particularly when considering issues of durability and reliability. The obtained simulation results are compared with those of a PID controller and it has been concluded that the reliability of comb drive can be improved using the developed SMC.

Key-Words: - MEM actuators, Electrostatic Comb drive, Sliding mode controller, Reliability

1 Introduction

Numerous research studies have been conducted on comb drives, which are electrostatic actuators mainly used in Microelectromechanical Systems (MEMS). Comb drives (CDs) have been used for static actuation of friction test structures, micro grippers, force balanced accelerometers, micro mirrors etc. [1], [2], [3], [4], [8], [9]. Studies on MEMS actuators in the literature have concentrated mostly on processing technology and mechanic design optimization [6], [10]. Not much research has been reported on control techniques related to MEMS [8], [9].

As it is well known, reliability and durability is a vital topic in MEMS technology [12]. The problem applies very strongly to comb drives, in which a crash of the moving part with the static section will cause the scattering of small particles. These particles can give rise to short circuits or lead to problems preventing the proper operation of the mechanical system. To minimize the possibility of such errors, the motion of the moving part must be controlled to avoid undesirable oscillations and collision.

The major contribution of this study is the development of a robust nonlinear controller for the motion control of MEM comb drives. For this purpose, a chattering free sliding mode controller (SMC) is developed and its performance is compared with that of classic PID control. The results demonstrate a smooth, vibration-free and robust performance in the face of parameter and model uncertainties.

The study is organized as follows: After the introduction in Section I, the mathematical model of the MEM comb drive is given in Section II; Section III gives the results obtained with a PID controller, while Section

IV gives a description of the chattering free SMC as obtained for this particular system. The results obtained with SMC are also given in this section. Finally, our conclusions are listed in Section V.

2 Mathematical Model

The most common driving mechanism for micro actuators is electrostatic force. The electrostatic force, F, generated in comb drive actuators given in Figure 1, can be expressed as follows:

$$F = \frac{N \varepsilon h V^2}{2}\left[\frac{w}{(L-x)^2} + \frac{1}{g}\right] \tag{1}$$

where,
N: number of tooth
ε : dielectric constant,
a: gap distance [m],
h: electrode depth [m],
w: electrode width [m],
x: displacement of the moving part [m],
V: applied voltage [V].

With the consideration of the mechanical system in Figure 1, the following equation of motion can be obtained:

$$F = \frac{N \varepsilon h V^2}{2}\left[\frac{w}{(L-x)^2} + \frac{1}{g}\right] = M\ddot{x} + B\dot{x} + Kx$$
$$0 \le x \le L \tag{2}$$

where,
M: mass of the moving part of the system,
B: damping coefficient,
K: spring coefficient.

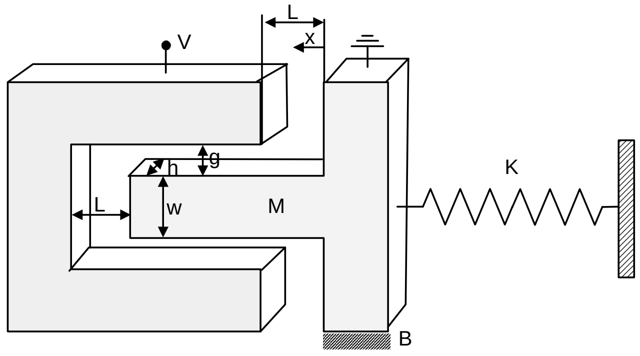

Figure 1- Schematic diagram of a MEM comb drive

As can be seen from the equation of motion in (2), the system is highly nonlinear.

3 Robust Control of MEM Comb Drives

To avoid collision between the moving and stationary parts of the comb drive, the motion of the moving part must be controlled to achieve a displacement response that is fast, but has no overshoot or vibrations. Considering the mechanical structure of the comb drive and its operation, it is obvious that the system will be exposed to a variety of parameter variations (mostly, temperature related) and model uncertainties due to the Coulomb, viscous and stiction friction. For this purpose, in this study, a chattering free sliding mode controller (SMC) is proposed in order to achieve a robust, critically damped response in the face of the above mentioned uncertainties.

4 Control of a Comb Drive using SMC

To achieve the robust position control of the moving part, a chattering free sliding mode controller is developed, which maintains the error dynamics of the output response on a prescribed surface in spite of parameter and model uncertainties.

To this aim, the sliding surface is chosen as,

$$\sigma = \dot{e} + ce \tag{3}$$

with

$$e = x_{ref} - x \text{ and } \dot{e} = \dot{x}_{ref} - \dot{x}$$

x_{ref}: desired displacement of the moving part (here it is equal to L) [m]
x: actual displacement of the moving part [m]
Thus,

$$\dot{\sigma} = \ddot{x}_{ref} - \ddot{x} + c(\dot{x}_{ref} - \dot{x}). \tag{4}$$

Substituting (2) into (4) and rearranging;

$$\dot{\sigma} = \left(\frac{\beta}{M} - c\right)\dot{x} + \frac{K}{M}x - \frac{N \varepsilon h V^2}{2}\left[\frac{w}{(L-x)^2} + \frac{1}{g}\right] \tag{5}$$

Define,

$$V^2\left[\frac{w}{(L-x)^2} + \frac{1}{g}\right] = u$$

$$V = \sqrt{u\left[\frac{w}{(L-x)^2} + \frac{1}{g}\right]} \tag{6}$$

Consequently, (5) can be rewritten as,

$$\dot{\sigma} = (\frac{\beta}{M} - c)\dot{x} + \frac{K}{M}x - \frac{N\varepsilon h}{2M}u \tag{7}$$

Next, the control input, u, is calculated to take the system dynamics to the prescribed surface and maintain it there. If $u = u_{eq}$,

$$\sigma = 0 \ \text{ and } \ \dot{\sigma} = 0 \tag{8}$$

Thus,

$$\dot{\sigma} = (\frac{\beta}{M} - c)\,\dot{x} + \frac{K}{M}x - \frac{N\varepsilon h}{2M}u = 0, u = u_{eq} \tag{9}$$

From (9), it can be concluded that

$$\dot{\sigma} = \frac{N\varepsilon h}{2M}(u_{eq} - u) \tag{10}$$

For the determination of the control input, u, a Lyapunov function is selected in the following form:

$$V = \frac{1}{2}\sigma^2 \tag{11}$$

$$\dot{V} = \sigma\dot{\sigma} \tag{12}$$

To ensure the negative positiveness of $\dot{V}$ in (12), select

$$\dot{\sigma} = -D\sigma \tag{13}$$

By discretizing and rearranging (10), the following equation is obtained:

$$u_{eq}(k-1) = u(k-1) + \frac{2M}{N\varepsilon h}\left[\frac{\sigma(k) - \sigma(k-1)}{T}\right] \tag{14}$$

From (10) and (13),

$$u_{eq}(k) = u(k) - \frac{2M}{N\varepsilon h}D\sigma(k) \tag{15}$$

is obtained. At this point, the assumption that the average value of equivalent control does not change between two sampling period when a fast switching operation is involved, leads to the following approximation;

$$u_{eq}(k) = u_{eq}(k-1) \tag{16}$$

Thus, (14) and (15) can be combined and rearranged resulting in the following relationship:

$$u(k) = u(k-1) + \frac{2M}{N\varepsilon h}\left[\frac{(1+DT)\sigma(k) - \sigma(k-1)}{T}\right] \tag{17}$$

5 Simulation Results

To compare the performance of sliding mode controller and PID controller, simulations are performed for the control of the comb drive using MUMPS process design rules and Matlab/Simulink®. The first set of simulations are performed for the PID controller. As can be seen in Figure 2, even a well-tuned PID control gives rise to vibrations in the output response.

On the other hand, the simulation results obtained with the chattering free SMC demonstrate an improved output performance with no vibrations.

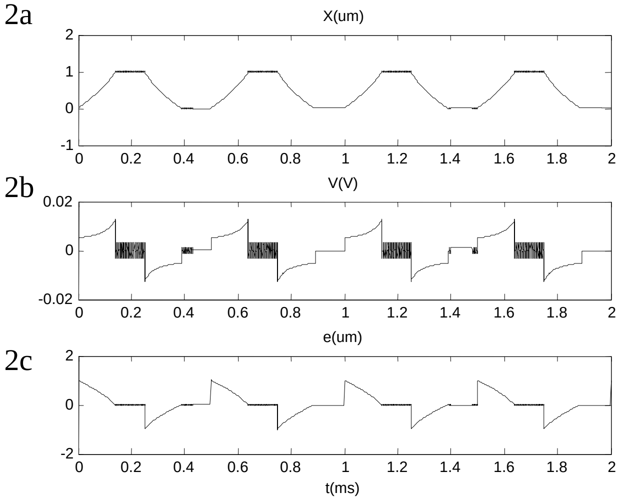

Figure 2. Simulation results for the control of the MEM comb drive using PID controller (a) rotor displacement, (b) applied voltage on the actuator, (c) distance between rotor and stator.

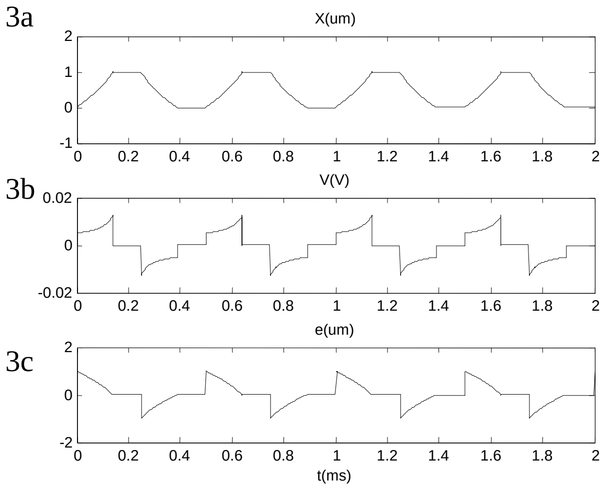

Figure 3 Simulation results for the control of the MEM comb drive with SMC (a) rotor displacement, (b) applied voltage on the actuator, (c) distance between rotor and stator.

6 Conclusion

Most MEMS devices can only work for only several a short duration because of reliability problems like fatigue, stiction, etc. Therefore reliability is a very important issue for MEMS devices. Fatigue resistant alloys or developing different process structures are some approaches taken in the literature to resolve this problem. However, both methods involve process technology and hence, are rather costly.

In this study, a control based approach is offered as a more economical and flexible solution to the problem of reliability in MEM comb drive operation. The idea of improving the performance of a MEMS device using integrated electronic control techniques is a novel idea and to the author's best knowledge, this study is the first known application of this idea.

However, this technique also gives rise to some costs; i.e. for the new die which contains the electronic parts of the system. Fortunately, the fabrication cost of electronics is almost negligible when compared with the costs involved with changing process.

The study also shows that the use of a nonlinear controller is more effective for the system when compared with a standard linear PID controller, due to the nonlinear nature of the comb drive dynamics. With the use of the SMC, the collision between the rotor and stator is considerably softened or eliminated, thereby decreasing system faults and increasing reliability as well as the life span of the MEM comb drive at a reduced cost.

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