'88 KACC 1988. 10. 21~22

SERVO CONTROL SYSTEM OF ELECTROSTATIC MICRO-ACTUATOR FOR MICRO ROBOTS

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Abstract: In mechanical systems in which the dynamics of armatures is dominated by electrostatic forces, motions will generally be unstable. This paper deals with the control problems of this kind of micro electrostatic device systems. In these systems, the mass of micro mechanical parts is so small that the inertia term in the equation of motion is negligible. However, nonlinear terms, such as friction and driving force, become dominant. The purpose of this paper is to realize the stable motion without delay and overshoot etc. A micro-mechanical system used in this paper consists of a plane wafer with striped electrodes converted with an insulation layer and thin cylindrical roller is placed over on it. The performance of motions is confirmed by some simulations.

1. Introduction

Small or micro electro-mechanical systems can often deliver numerous performance advantages over their large-scale counterparts. Especially, the electrostatic drive is more advantageous for micro scale devices than traditional electromagnetic devices [1].

The idea of electro-static drive has a long history but the application was limited by its low power density. As the micro-machining techniques developed rapidly, the electrostatic drive attracted renewed attention. Silicon micro-machining techniques for VLSI manufacturing have enabled us to fabricate precise electrode patterns and good insulation films. Electrostatic actuators on silicon wafers are not only light and compact but suitable for integrated "smart" actuators and the element of micro manipulators.

The electrostatic force is a surface force and needs only two thin electrode separated by an insulator. The source of the electrostatic force is charge. We only need to keep the voltage across electrodes to produce steady force. In these systems, the static friction and dynamic friction play a large role in mechanical motion. It is difficult to control the precise micro-order positioning, keeping the stable condition. The purpose of this paper is to realize the stable motion without delay and overshoot.

This paper is organized as follows. The configuration of an ESLAC (electrostatic linear actuator), used in this paper, is described in section 2. The driving force of the system and mathematical model are established in section 3. Section 4 shows the result of the experimental studying, with simple closed loop control, in order to confirm the control performance of this kind of actuator. A strategy for servo controller of the micro robot system with unknown friction model is presented in section 5. The result of some simulations is shown in section 6. Some conclusion are given in section 7.

2. Configuration of the Electrostatic Linear Actuator [2]

The driving mechanism of the actuator is schematically shown in Figure 1 and 2. A cylindrical conductor (roller) is placed on a plane wafer. The axis of the roller is parallel to the striped electrodes which are embedded in an insulation layer on the wafer surface. The striped electrodes on one side of the roller are kept at a high potential with respect to the roller hence an electric field is formed between the roller and those electrodes. The electrostatic force attracts the roller and makes it roll. As the roller passes over a striped electrode, that electrode is discharged and another electrode, in the forward direction, is charged up to keep the movement. The configuration of an ESLAC which consists of rollers inserted between a C-shaped actuator and a slider is shown in Figure 3.

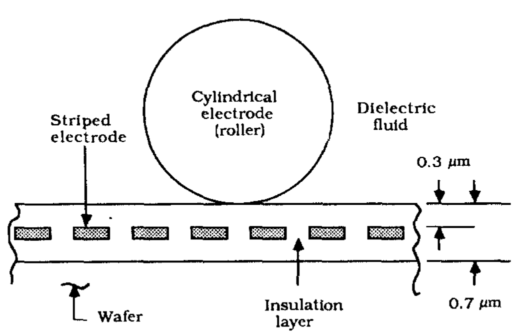

Fig. 1 Cross section of the ESLAC.

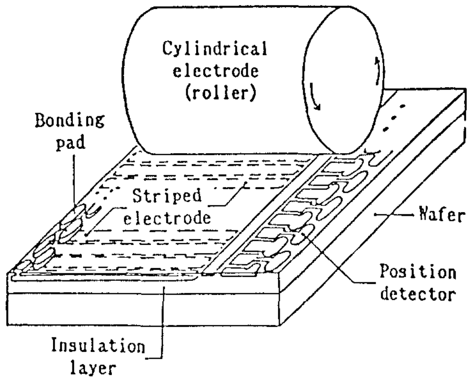

Fig. 2 Driving mechanism of the roller.

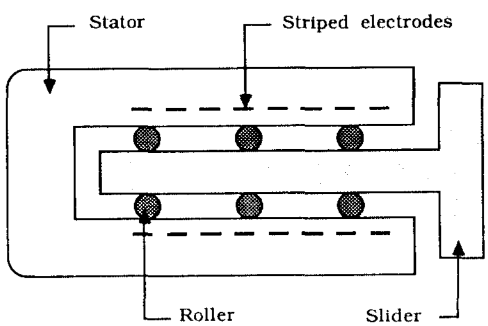

Fig. 3 Cross section of the C-shaped electrostatic drive mechanism.

3. Driving Force and Mathematical Model

Once electric field on the driving electrode is determined, it is rather easy to obtain the driving force **F** by the formula :

$$\mathbf{F} = \int_S d\mathbf{F} \tag{1}$$

$$d\mathbf{F} = (\varepsilon/2)E^2\mathbf{n}ds \tag{2}$$

where ε is the permittivity of the media, S is the electrode surface, and **n** is the normal vector of the surface. The integration (1) should be performed for each vector component.

The electric field can be determined by either analytical or numerical method[2]. The analytical method is applicable to rather simple geometries. The solution, if any, is very useful to have rough estimation.

In the case of ESLAC, the roller-to-plane electrode system is simplified and replaced by a cylinder-to-plane system as shown in Figure 4. The field in the cylinder-to-plane system can be calculated by either the conformal transformation or the image method. The field strength E on the cylinder, the driving force F_x, and the sticking force F_y are given as follows:

$$E(\theta) = \frac{\sqrt{1+2\alpha}}{\alpha(1+2\alpha\cos^2\frac{\theta}{2})[\ln\{(\sqrt{1+2\alpha}+1)^2/2\alpha\}]} \cdot \frac{U}{d} \tag{3}$$

$$F_x = \frac{\varepsilon l U^2}{r[\ln\{(\sqrt{1+2\alpha}+1)^2/2\alpha\}]^2} \tag{4}$$

$$F_y = \frac{\pi\alpha}{2\sqrt{1+2\alpha}} F_x \tag{5}$$

where θ is the angle shown in Figure 4, α equals to r/d, r and l are the radius and the length of the roller, and d is the insulation thickness.

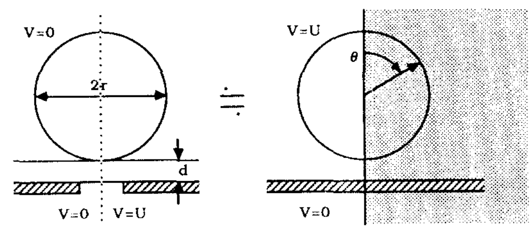

Fig. 4 Substitution by a cylinder-to-plane system for analytical solution.

The numerical method is more versatile. We can determine almost any field with three dimensional combination of electrodes and dielectrics. The finite element method, the charge simulation method, and the surface charge method are most commonly used. For some methods computer codes are available. The field distribution on a roller obtained by the surface charge method is shown in Figure 5.

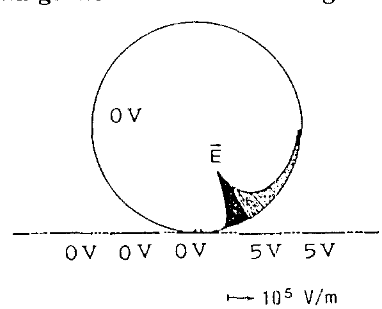

Fig. 5 Field distribution on a roller obtained by surface charge method.

The kinetic of ESLAC with no payload is calculated based on Figure 7. Figure 6 shows an ESLAC consisting of a plate and rollers on a substrate. The mass, the radius, and the moment of inertia of roller are M, r, and J respectively. The mass of the plate per roller is m. Only the movement in the horizontal direction (parallel to the substrate) is analyzed. The horizontal forces on the roller are the electrostatic driving force, F_x, the frictional force, F_f between the roller and the substrate, and the reactive force, F_r', the counterpart of which accelerate the plate.

$$F_f(t) = \mu_1 N(t) \mathrm{sign}\{\dot{x}_1(t)-\dot{\theta}(t)\} \quad (6)$$

$$Fr'(t) = \mu_2 mg\,\mathrm{sign}\{\dot{x}_1(t)-\dot{x}_2(t)\} \quad (7)$$

$$T(t) = \mu_1 N(t) r \quad (8)$$

$$M\ddot{x}(t) = F_f(t) - F_r'(t) \quad (9)$$

$$J\ddot{\theta}(t) = T(t) - F_r'(t) \quad (10)$$

$$N(t) = (M+m)\mathbf{g} + F_y(t) \quad (11)$$

where, N(t) is drag force, T(t) is driving torque, μ_1 is motion friction coefficient between the roller and the substrate, μ_2 is one between the roller and the plate, and they contain the sliding and rolling friction coefficients respectively. and **g** is gravitational acceleration.

Note that the roller rotates without slip and that the plate moves twice as fast as the roller. The equation of motion for the roller is given as follows:

$$\frac{d^2x_1}{dt^2} = \frac{F_x}{M+4m+J/r^2} \quad (12)$$

If the roller is a thin pipe, the moment of inertia J is equals to Mr^2. Substituting J into equation (12), it gives:

$$\frac{d^2x_1}{dt^2} = \frac{F_x}{2(M+2m)} \quad (13)$$

It means the effective mass of the actuator is the sum of twice the mass of the roller and four times that of the plate.

In this paper, we assume that the motion between the plate and roller does not slide, then the equation (7) is changed as follows :

$$F_r'(t) = 2m\ddot{x}_1(t) \quad (14)$$

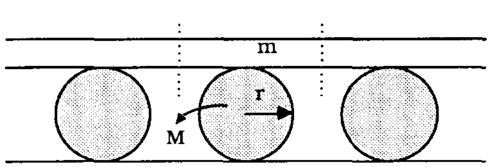

Fig. 6 Model of ESLAC to calculate its kinetics.

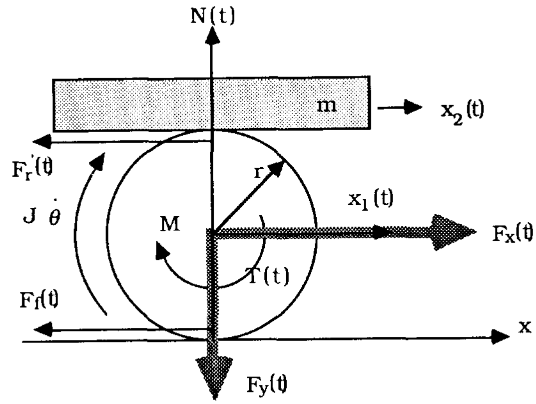

Fig. 7 Force diagram acting to the roller

4. Experimental Studying with Simple Closed Loop Control [5]

In this section, the simple experiment is carried out in order to confirm the control performance of this kind of actuator. The block diagram in Figure 8 shows an experimental circuit for simple closed loop control. A 16-bit micro computer switched on and off the driving voltage up to 120 volts on each line electrode through a photo-coupler. Shorter pulses compared to the driving voltage were applied to each electrode sequentially. The pulses traveled through capacitance coupling to the roller and were detected across an inductance inserted between the grounding electrode and the ground. The largest pulse was observed when the pulse was applied to the line electrode just beneath the roller. The delay between the initiation of the sequence and the detection of the largest pulse showed the roller position. The computer energized the appropriate electrodes according to the position.

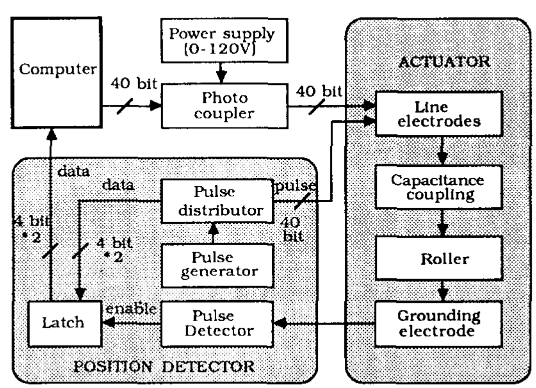

Fig. 8 Block diagram of the experimental setup for the simple closed loop control.

The movement of the roller was like the linear stepping motor. Each step was equal to 67μm, the total width of a line and a space. The response to a sudden increment of the reference input is shown in Figure 9. The delay and reverse response at $0 < t < 0.5$ sec were due to the static friction. Once the roller started moving, it passed 10 steps (670μm) in 250ms. Small oscillation was observed before the roller stopped. At t=1.5 sec, some disturbance came in. The roller returned to the desired position in 200 ms after the disturbance.

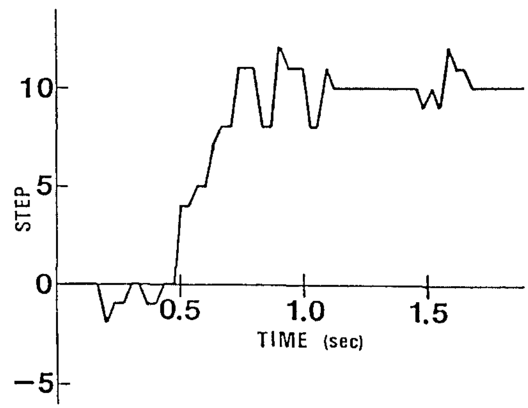

Fig. 9 Response to 10-step increment of reference input.

5. Closed Loop Servo Controller

Although the operation of micro actuator is similar to linear stepping motors in principle, a closed loop control system is necessary to obtain the stable motion performance against the nonlinear effects of the micro electro-mechanical system. According to the result of simple experiment, the response for the step input occurs the time delay and overshoot. It is not good response performance. Therefore, it is necessary to control the stable motion without time delay and overshoot etc.

So the acceleration control is proposed as a servo controller for these system. This servo system has an excellent performance of disturbance suppression, because the total acceleration including the load torque and various kind of frictional torques can be controlled directly [6]. The acceleration of the whole system is determined by the total driving force including actuator torque and any kind of frictional torques, i.e. static friction and dynamic friction etc.

Design of servo controller

The schematic of principle elements of ESLAC controller is shown in Figure 10. The control loop can be separated into five basic components :

The velocity estimator, the acceleration calculator, the control law and drive, the physical system, and sensor. The actual position (X_{act}, it means the $x_1(t)$ of Figure 7) of the roller was determined by measuring the capacitance between the roller and each electrode. The actual position signal is then differentiated to produce the estimated velocity which is obtained through a first-order filter. The acceleration calculator provides the actual acceleration signal from the estimated velocity. Its transfer function is as follows :

$$\frac{\ddot{x}_{est}(t)}{\dot{x}_{est}(t)} = \frac{s}{1+T_a s} \qquad (15)$$

The function (15) describes the imperfect differentiation, where T_a is time constant, and can be designed to be a very small value, for example, a few hundred micro-seconds.

The input to the acceleration controller is the acceleration error with respect to its reference $\ddot{x}_{des}(t)$, generated by the desired position x_{des}. The control law is given by :

$$u(t) = K_a\{\ddot{x}_{des}(t) - \ddot{x}_{est}(t)\} \qquad (16)$$

where $\ddot{x}_{est}(t)$ is the acceleration calculated by the estimated velocity, and K_a is a proportional gain.

The controller prescribes a driving force to be applied to the roller. The potentials to be applied (Di) to each electrode sequentially are generated according to the driving force.

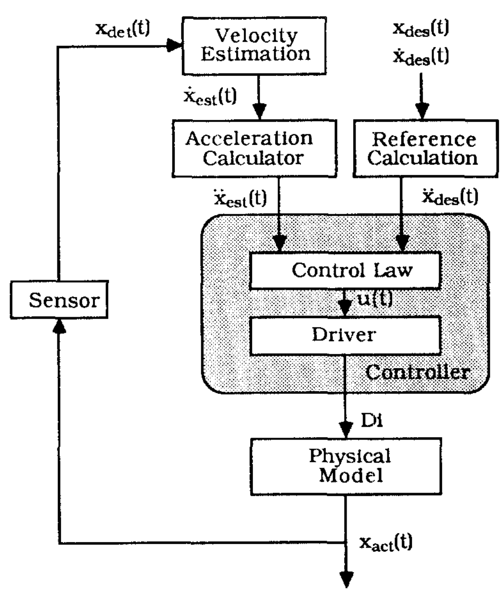

Fig. 10 Block diagram of the ESLAC controller.

6. Simulation Results

In this simulation, five electrodes near the roller is used in order to generate the driving force. However, 0 volt is always supplied to the electrode just beneath the roller. According to the position of the roller, the driving voltage is applied to the appropriate electrode.

In order to confirm the validity of the proposed acceleration controller. the desired trajectory response of the system is examined by the simulation. The desired motion pattern of the roller and its tracking response are shown in Figure 11 and 12 respectively. It shows perfect tracking capability as there is almost no tracking error between the desired trajectory and the trajectory response of the system.

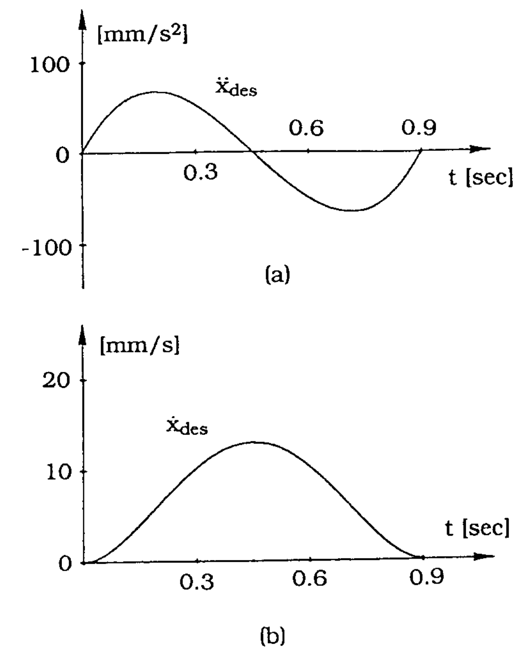

Fig. 11 Desired motion pattern of the roller
(a) Acceleration. (b) Velocity

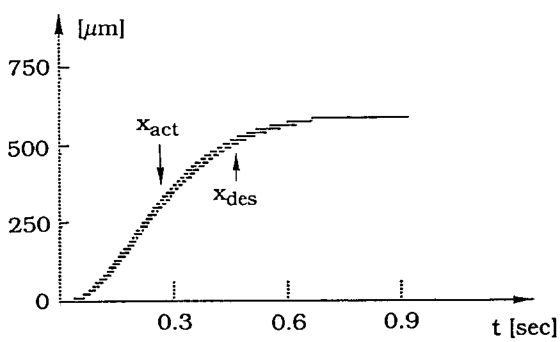

Fig. 12 Tracking response of the roller to the desired trajectory

7. Conclusion

In this paper, the control problems of micro electrostatic device systems which are dominated by the various kinds of friction are discussed. we proposed the acceleration controller for these systems, and confirmed the validity of the proposed controller. The acceleration controller overcomes the frictional problems, and it produced the improved performance in tracking response and stability.

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