정전부상장치의 비선형성을 고려한 스위칭 제어기의 설계

Design of a Nonlinear Switching Controller for Electrostatic Suspension System with Nonlinear Dynamics

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1. INTRODUCTION

In recent years, many electrostatic suspension systems have been studied and reported. The conventional electrostatic suspension systems based on PID (Proportional-Integral-Derivative) controller have been presented in [1, 2]. These systems used high-voltage amplifiers to generate the high control voltage in the order of kilo volt which is supplied to the electrodes. However, a major disadvantage of these systems is that the high-voltage amplifiers are relatively costly and bulky system components and they are critical factor in potential industrial applications. The electrostatic suspension systems based on switched voltage control scheme have been reported in [3, 4]. These systems do not deploy any high voltage amplifiers but require only single high voltage power supplies, therefore they can deliver a constant voltage of positive or negative polarity for an arbitrary number of individual stator electrodes that have to be controlled and the cost of the system is reduced significantly. However, the drawback of the above studies is that the damping force is not considered in design of a controller. It is known that the motion of small parts can be affected by the surrounding air significantly. The air presents a counter reactive force on the moving suspended object. The ever-present damping effect of the surrounding air would be increased when a plate was oscillating near a second surface due to the squeeze film action of the gas between the surfaces. The squeeze film damping will be more important than the drag force damping of air if the thickness of the gas film is smaller than one-third of the width of the plate. Therefore, in the contactless electrostatic suspension system where the suspended objects have large surface area and suspension gap is small, the squeeze film effect is the important damping effect on its dynamic behavior. In addition, despite the fact that electrostatic levitation system have unstable behavior and are described by highly nonlinear differential equations of electrostatic and damping forces, almost design approaches are based on the linearized model about a nominal operating point. In this case, the tracking performance deteriorates rapidly with the increase of deviations from the nominal operating point.

In this paper, a nonlinear switching control is proposed for electrostatic suspension system. The obtaining of switched voltage control law is based on the nonlinear equation of motion of the suspended object including the nonlinear damping force without using of linearization technique.

2. PRINCIPLE OF OPERATION

The electrostatic suspension system of a 1-dof (degree of freedom) based on switching controller can be designed as shown in Fig. 1. The system consists of a suspended object, an airgap sensor, stator electrodes, two high-voltage power supplies, switching circuits, and a controller. Two concentric stator electrodes, outer electrode E_p and inner electrode E_n, are provided by positive voltage ($+V_{ON}$ or $+V_{OFF}$) and negative voltage ($-V_{ON}$ or $-V_{OFF}$), respectively. Based on the measured position signal, the electrodes repeat charged-discharged by the on-off action of the switching circuits. In other words, switches SW_1 and SW_3 are closed while SW_2 and SW_4 are opened simultaneously so that the charge voltages $+V_{ON}$ and $-V_{ON}$ are applied to the outer and inner electrode, respectively. Similarly, the outer and inner electrode are provided by charge voltages $+V_{OFF}$ and $-V_{OFF}$ when switches SW_2 and SW_4 are closed while switched SW_1 and SW_3 are opened simultaneously, respectively.

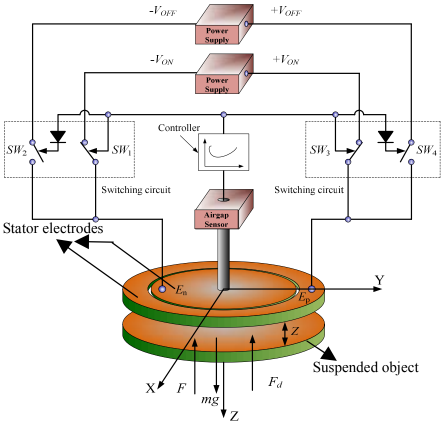

Fig. 1 1-dof electrostatic suspension system

3. NONLINEAR DYNAMIC MODEL

The various forces acting on the suspended object are the attractive electric force F, damping force F_d, and gravitational force. The nonlinear dynamic of 1-dof electrostatic suspension system are presented as follows [4]

$$m\ddot{z} = mg - \frac{3\pi\eta r_0^4}{2z}\dot{z} - \frac{\varepsilon A}{2}\left(\frac{V}{z}\right)^2 \qquad (1)$$

where z is a gap length, m is a mass of suspended object, V is a control voltage which is supplied to the electrodes, $\eta = 18.10^{-6}$ N.s/m^2 is a viscosity of air, $\varepsilon = 8.854.10^{-12}$ F/m is a permittivity, A is the area of electrode, and r_0 is the radius of suspended object.

4. DESIGN OF NONLINEAR SWITCHING CONTROLLER

The nonlinear state space of the electrostatic suspension system can be written as

$$\dot{z}_1 = z_2, \dot{z}_2 = g - k_1(z_2 / z_1^3) - k_2(u^2 / z_1^2) \qquad (2)$$

where z_1, z_2 are displacement and velocity of the suspended object, respectively. Coefficients $k_1 = (3\pi\eta r_0^4 / 2m)$, $k_2 = (\varepsilon A / 2m)$ are damping and electric coefficient, and $u = V$ is the control voltage.

We are interested in a control law that maintains the suspended object at an arbitrary position $z = z_0$. However, this equilibrium point of system is unstable, and so we look for a state feedback control law to stabilize the closed loop around the equilibrium point. We start by applying a coordinate transformation to translate the equilibrium point $(z_0, 0)^T$ to the origin. Let's define a new variables as $Z_1 = z_1 - z_0$, $Z_2 = z_2$, $U = u^2 - u_0^2$, where $u_0 = z_0\sqrt{g / k_2}$ is bias voltage at equilibrium point. The state space of the system in new variables can be written as

$$Z_1 = Z_2, \dot{Z}_2 = f(Z) + g(Z)U \qquad (3)$$

where

$$f(Z) = g - k_1 Z_2 /(Z_1 + z_0)^2 - g z_0^2 /(Z_1 + z_0)^2$$
$$g(Z) = -k_2 /(Z_1 + z_0)^2$$

The objective is to obtain the switching voltage control law which is applied to the electrostatic suspension system in order to make a realizable contacless suspension system. We define the switching surface as

$$s = Z_2 + \lambda Z_1 \text{, or } \quad s = z_2 + \lambda(z_1 - z_0), \lambda > 0 \qquad (4)$$

The time derivative of s is $\dot{s} = \dot{z}_2 + \lambda \dot{z}_1$. Then, we can write as

$$\dot{s} = f_1(z) + g_1(z)U + \lambda z_2$$

where $f_1(z) = g - k_1 z_2 / z_1^3 - g z_0^2$, $g_1(z) = -k_2 / z_1^2$

To evaluate stability, the candidate Lyapunov function is chosen as $V_1(z_1, z_2) = (1/2)s^2$, $\dot{V}_1(z_1, z_2) = s\dot{s} = s(f_1(z) + g_1(z)U + \lambda z_2)$ Evidently, the system is stable if $s = 0$. In case $s \neq 0$, the system is stable if condition $\dot{V}_1(z_1, z_2) < 0$ is satisfied. In order to obtain this required condition, the control law could be chosen as:

$a) U = 0 \;\; if \;\; s < 0$, the condition $\dot{s} > 0$ must hold to guarantee the stability of system. It means that

$$f_1(z) + \lambda z_2 > 0 \qquad (5)$$

$b) U = 1 \;\; if \;\; s > 0$, the condition $\dot{s} < 0$ must hold to guarantee the stability of system. It means that

$$f_1(z) + g_1(z) + \lambda z_2 > 0 \qquad (6)$$

It combines (5), (6) we can conclude that the system is stable with above switching control law if state space of the system is the element of set Δ which is defined as

$$\Delta = \{(z_1, z_2) \mid (f_1(z) + \lambda z_2 > 0) \cap (f_1(z) + g_1(z) + \lambda z_2 < 0)\}$$

However, the control law presented in (*a*), (*b*) is not valid for state space which is in the outside of the region Δ. In that case, the control law is found by using Lyapunov theory and guarantees asymptotic stability. The candidate Lyapunov function is chosen as the total mechanical energy of the system as

$$V_2(z_1, z_2) = (1/2) m z_2^2 + m g (h_0 - z_1) \qquad (7)$$

where h_0 is the distance from stator electrode to the ground. Evidently, $V_2(z_1, z_2)$ is always positive definite because the total mechanical energy could not be negative. The time derivative of V_2:

$$\dot{V}_2(z_1, z_2) = m(-(k_1 z_2^2 / z_1^3) - (k_2 z_2 / z_1^2) u^2) \qquad (8)$$

Since $z_1 > 0$, the derivative of $V_2(z_1, z_2)$ is negative value if

c) $u = 0$ when $z_2 \leq 0$

d) $u = 1$ when $z_2 > 0$

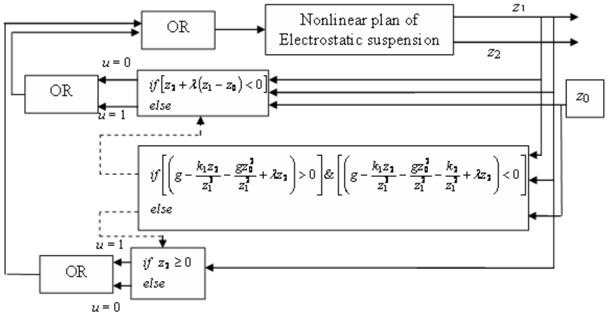

Fig. 2 The schema of nonlinear switching control

Finally, the schema of the nonlinear switching control for electrostatic suspension system is proposed as shown in figure 2. In case suspension is performed in vacuum environment, the damping coefficient k_1 is set at zero value.

5. SIMULATION RESULTS

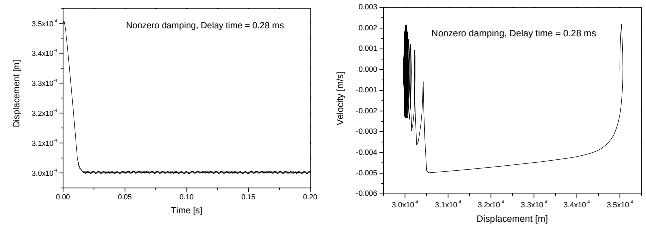

Fig. 3 Simulation results for suspension in ambient air of 4-inch silicon wafer

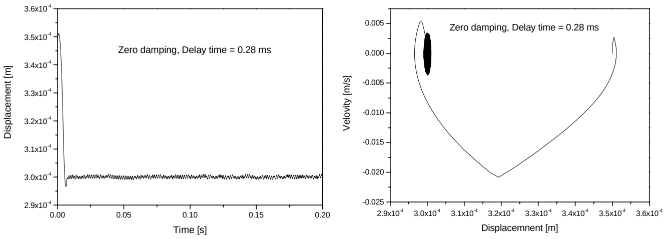

Fig. 4 Simulation results for suspension in vacuum environment of 4-inch silicon wafer

The MATLAB software package is utilized to simulate the suspension of 4-inch silicon wafer. The initial gap and the desired gap are set at 350 μm and 300 μm, respectively. The voltage V_{ON} set at 720 V and the voltage V_{OFF} set at 0 V. Figures 3, 4 provide the simulation results showing the gap fluctuation in ambient air and vacuum environment where time delay of switching circuit is 0.28 ms, respectively. In both two case of suspension, the magnitudes of vibration of suspended object were very small.

6. CONCLUSION

The position control of silicon wafer in the contacless electrostatic suspension system having nonlinear dynamics based on nonlinear switching controller is presented. The stability of the controller is completely analysed. The simulation results presented for a 4-inch silicon wafer in vacuum and ambient environment show the effectiveness of the proposed method.

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