시간지연 제어기를 이용한 진공환경에서의 정전부상시스템에 관한 시뮬레이션

Simulation of Electrostatic Suspension System Based On Delay Controller for Use in Vacuum Environment

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1. INTRODUCTION

Many electrostatic suspension systems have been studied and reported in recent years. The conventional electrostatic suspension systems utilize high-voltage amplifier in a PID (proportional-integral-derivative) based feedback control scheme to generate the high voltage which is supplied to the electrodes [1], [2]. However, a major disadvantage of these systems is that the high-voltage amplifiers are relatively costly and bulky system components which are critical factor determining potential industrial application. The electrostatic suspension systems where suspended objects having a large surface area/thickness ratio are used, which are based on switched-voltage control type and operates according to a relay feedback control, have been studied to reduce the identified cost and complexity problem of conventional systems [3],[4]. However, in the electrostatic suspension system for silicon wafer based on simple on-off switched voltage control scheme, the amplitudes of vibration of silicon wafer were large and the suspension system need a presence of a large damping force to stably suspend an object at reference gap. It means that this system could not be used in vacuum environment because a damping force does not exist in vacuum. The electrostatic suspension system using time optimal control has been reported as well. However, the stability of the system is not considered in this study.

This paper presents the electrostatic suspension system based on delay controller which is a kind of switched-voltage control type. Sufficient conditions for stability including time delay and initial value of the object are found. It is shown that the electrostatic suspension system is stable if the delay time and initial values of the system are less than identified critical values. In addition, the critical time delay of this system can be evaluated based only on desired suspension gap of silicon wafer. By using this control scheme, the amplitude of vibration of suspended object can be zero and along with the fact that the heavy objects can be levitated in vacuum environment [2], the system is expected to be applied to contacless handle objects in the apparatus for spacecraft and semiconductor equipments operated in where air does not exist.

2. PRINCIPLE OF OPERATION

The electrostatic suspension system of a 1-DOF (degree of freedom) 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.

3. DYNAMIC MODEL

The various forces acting on the suspended object in vacuum are the attractive electric force F, and gravitational force. The damping force F_d is vanished. The dynamic of 1-DOF electrostatic suspension system and the linearization equations are presented in [4] as follows

$$m\ddot{z} = k_s z - k_V V \tag{1}$$

where z is linearization gap length, m is mass of suspended object, k_s and k_V are linearization constants. The reader can find them in [4]. V is control voltage which is supplied to the electrodes.

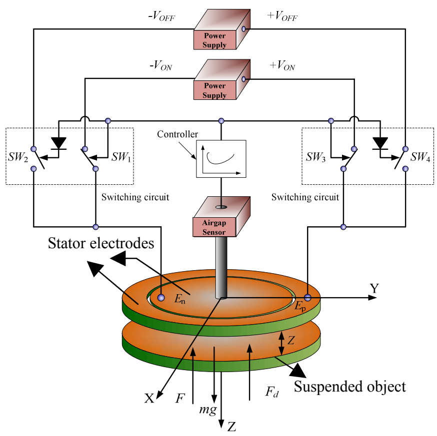


Fig. 1 1-DOF electrostatic suspension system

4. DESIGN OF DELAY CONTROLLER

For the purpose of suspension at reference gap, we define the state space as follows:

$$\dot{z}_1(t) = z(t) - z_0,\ z_2(t) = \dot{z}(t),\ u(t) = V \tag{2}$$

where $z_1(t)$ is the position error with z_0 being the desired final position. The state space of electrostatic suspension in term of time delay can be written as

$$\dot{z}_1 = z_2, \dot{z}_2 = (k_s/m)z_1 - (k_V/m)u(t-\tau) \tag{3}$$

where τ is delay time. Let's $\omega_n = \sqrt{k_s/m}$, $k = k_s/k_V$, and we define a new variable y as $y = P^{-1}z$ where $P = \begin{bmatrix} 1 & 1 \\ \omega_n & -\omega_n \end{bmatrix}$.

We obtained two separate differential equations as

$$\dot{y}_1 = \omega_n y_1 - (1/\beta)u(t-\tau) \tag{4}$$

$$\dot{y}_2 = -\omega_n y_1 + (1/\beta)u(t-\tau) \tag{5}$$

where $\beta = 2k/\omega_n$. Clearly, the system (4) is unstable. We define an feedback control in form $u(t-\tau) = \beta sign(y_1(t-\tau))$.

The eq (4) becomes

$$\dot{y}_1 = \omega_n y_1 - sign(y_1(t-\tau)) \quad (6)$$

Let us computed a constant $A > 0$ for which the system (6) with a initial function $\varphi(t) = A$, $t \in [-\tau, 0]$, has stable periodic solution for $t > 0$. Since $\varphi(t) = A > 0$, $t \in [-\tau, 0]$, before the switching moment we have that

$$y_1 = 1/\omega_n + (A + 1/\omega_n)e^{\omega_n t} \quad (7)$$

From this equation we can conclude that the function $y_1(t)$ could be change its sign which is required condition for periodic if and only if the conditions $A - 1/\omega_n < 0$ is satisfied. In this case, we can write the above equation for new variable θ, which is the root of the equation $y_1(\theta) = 0$, in form $e^{\omega_n \theta} = (1 - \omega_n A)^{-1}$

The periodic characteristic of function $y_1(t)$ leads to the following equation $y_1(\tau + \theta) = -A$. It implied that

$$A = (e^{\omega_n \tau} - 1)[\omega_n]^{-1} \quad (8)$$

Since $A - 1/\omega_n < 0$, we obtained as $e^{\omega_n \tau} < 2$ and the critical time delay is defined as $\tau_{cr} = \ln 2/\omega_n$. This equation implied that for any positive value ω_n, we can choose a time delay $\tau < \tau_{cr}$ for which there exist zero frequency stable periodic modes.

Next, we find the relationships between the time delay and the initial values to ensure the periodic stable of the system. We assume $y_{1s}(t)$ is a solution of the system (6) with the initial function values as $y_{1s}(0) > 0$, $t \in [0, \tau]$. It implied that

$$\dot{y}_{1s}(t) = -1 + \omega_n y_{1s}(t) < 1 + \omega_n y_{1s}(t) \quad (9)$$

We defined a new variable $\omega(t)$ which is a solution of differential equation that $\dot{\omega}(t) = 1 + \omega_n \omega(t)$ and the condition $\omega(0) = y_{1s}(0)$ is satisfied. It is known, by Gronwall's inequality, that $y_{1s}(t) \le \omega(t)$. The latest inequality leads to

$$|y_{1s}(0)| \le (2 - e^{\omega_n \tau})(\omega_n e^{\omega_n \tau})^{-1} \quad (10)$$

Returning on electrostatic suspension system, we proposed the control law as

$$\begin{aligned} &if \quad sign(z_2(t-\tau) + \omega_n z_1(t-\tau)) > 0 \ then \ V = V_{ON} \\ &if \quad sign(z_2(t-\tau) + \omega_n z_1(t-\tau)) < 0 \ then \ V = V_{OFF} \end{aligned} \quad (11)$$

The sufficient conditions for stability of system are found as

$$\tau < \tau_{cr} = \ln 2/\sqrt{z_0/2g}\ , |z_1(0)| < 2(2 - e^{\tau\sqrt{k_s/m}})[e^{\tau\sqrt{k_s/m}}\sqrt{k_s/m}]^{-1} \quad (12)$$

where τ_{cr} is a critical time delay, and $z(0)$ is initial position of suspended object. Figure 2 shows the influent of desired suspension gap on critical time delay.

5. SIMULATION RESULT

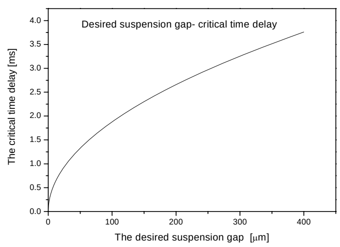


Fig. 2 The influent of desired suspension gap on critical time delay

The MATLAB software package is utilized to simulate the suspension of 4-inches silicon wafer. The initial gap and the desired gap are set at 350 μm and 300 μm, respectively. The voltage V_{ON} set at 660 V and the voltage V_{OFF} set at 180 V. Figure 3 provide the simulation results showing the gap fluctuation with time delay 0.28 ms and 0.4 ms, respectively. The amplitudes of vibration of silicon wafer are extreme small. A family of trajectories obtained for widely difference time delay with suspension gap 300 μm is also presented in Fig. 4. The critical delay time is obtained from eq (12) in that case is 2.7 ms. It is noted that this value is obtained by using linearization equations of nonlinear electrostatic force. However, the simulation results are obtained by using the MATLAB software where the nonlinear plan of electrostatic suspension system is used.

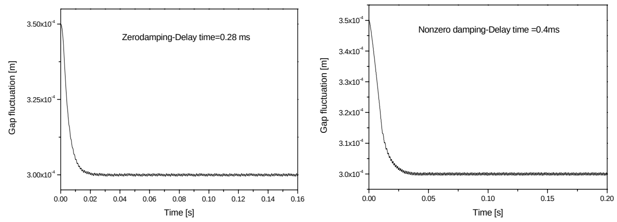
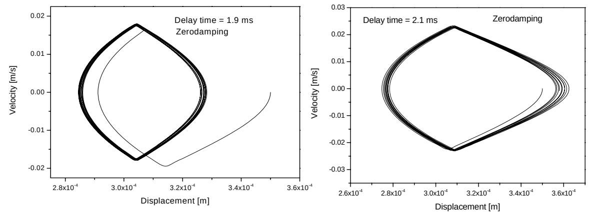


Fig. 3 Gap fluctuation of silicon wafer in vacuum environment



a) Stable state when time delay = 1.9 ms

b) Unstable state when time delay = 2.1 ms

Fig. 4 Trajectories in phase plane with suspension gap of 300 μm

Therefore, the true critical delay time is less than the evaluated value which is obtained from eq (12) and it has value of 2.1 ms. Figure 4a provided the stable state of suspension system in vacuum environment when delay time is 1.9 ms and the system will be unstable when delay time is 2.1 ms as shown in Fig. 4b.

6. CONCLUSION

The position control of silicon wafer in the contacless electrostatic suspension system based on a delay controller is presented. The stability of the controller is completely analysed. Sufficient conditions for stability including time delay and initial value of the suspended object are found. The critical time delay, maximum admissible value of time delay to ensure the system is stable, which depended only on suspended gap of the electrostatic suspension system is also shown in this paper. The simulation results presented for a 4-inchs silicon wafer in vacuum environment show the effectiveness of the proposed method.

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