Tracking Control of Nanopositioning System Using Proportional and Double Integral Action

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Abstract - *Precision control and manipulation of devices and materials at nanoscale is known as nanopositioning, a key requirement of nanotechnology. Nanopositioners are precise mechatronics systems designed not only to move or position a sample at some desired position with nanometre accuracy and repeatability but also to resolve adjacent positions of sample that are separated by less than a nanometre. High precision, large travel range with very high resolution, fast response with no or very little overshoot and high bandwidth are desired characteristics of nanopositioners. This paper presents the identification of nanopositioning device consisting of flexure stage for motion of sample and piezoelectric crystal as both sensor and actuator. Open loop behaviour of the nanopositioning device on the basis of time and frequency responses is plotted and analyzed.*

Nanoscale path planning and motion control of the sample are essential in nano manufacturing application such as micro-stereo-lithography (µSTL), dip pen nanolithography (DPN) and scanning application for imaging and manipulation of nanoscale surface phenomena. This paper aims at nanoscale path planning and motion control of sample. For this purpose, this paper describes the identification of motion trajectories commonly used in industrial application along with the challenges in optimal path planning to meet the nanoscale motion control objective and to achieve precise positioning and maximum throughput simultaneously. Proportional (P), proportional integral (PI) and proportional double integral (PII) controllers are simulated and implemented to obtain the accurate path tracking of the desired path. Then a comparative study of PI and PII controller on the basis of time response is given to show which controller is better. Simulation results for the performance analysis are carried out in MATLAB.

Key Words: Nanotechnology, Nanopositioning, Piezo-actuators, scanning, closed loop system, PI controller; PII controller, Tracking control.

1. INTRODUCTION

Today the demands of design and manufacture of miniature devices have been increasing in both research laboratories and industries. The demand and ability to view and manipulate structures/ devices/ systems at a nanoscale level has opened the possibilities of entire new area of scientific endeavour [1,2]. The size of devices continues to decrease in the nanometer scale size. The important factor that limits the manufacturing precision is the manipulation of the object at the nanoscale. Nanotechnology is the understanding and control of matter at the nanoscale where unique phenomena enable novel applications. It is the design, characterization, production and application of structures, devices and systems by controlling shapes and size at nanometer scale (atomic, molecular, and macromolecular scale) that produces structures, devices, and systems with at least one novel/superior characteristic or property [3,4]. The ability to image, control and measure at nanoscale is fundamental to nanotechnology Research and Development (R & D). Therefore, further progress in research in all area of nanotechnology request for the high precision positioning device which would ensure the nanometric accuracy of the positioning with high bandwidth [5].

The ability to image, control and measure at nanoscale is fundamental to nanotechnology research and development. It is widely recognized that one of the key requirement of nanotechnology is the nanopositioning. Nanopositioning is the precision control and manipulation of devices and materials at nanoscale with incredible accuracy [5]. The applications of nanopositioners are to Position -and-Hold the sample and Scanning of the desired path. For position-and-hold applications, the nanopositioner have to put an object at a precise position and require it to remain there for extended periods of time. For this application, only the final position is important, not the path taken to reach that position. The requirements of the nanopositioners for such applications are high thermal stability and very low long-term drift [3,5-6]. For scanning applications, optimization for travel speed and precision are required. The nanopositioners must be able to reach the required position rapidly and settle down at the required position in a short time. The system is moved along a pre-defined trajectory in time and space, and each position along this path is important.

2. MODELING OF NANOPOSITIONING SYSTEM

A nanopositioning device consists of a sensor to measure the position of the nanopositioning stage (flexure guided mechanisms) and an actuator is used to convert the electrical signal produced by the controller in the physical signal needed by the positioning system having nano scale resolution [4,7-8] The block diagram of nanopositioning system is shown in figure 1.

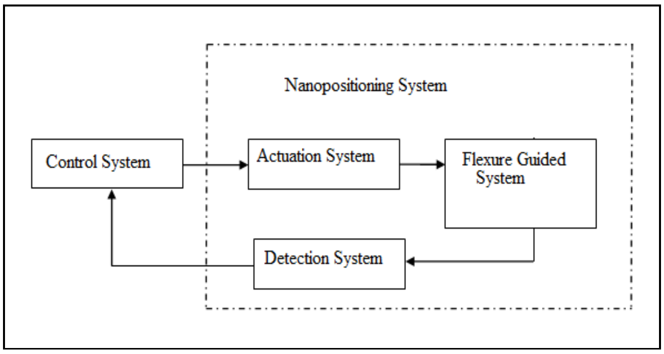

Figure 1 Block Diagram of Nanopositioning System

Nanopositioning devices ubiquitously use piezoelectric actuators, as such actuators enable fast and frictionless motion [4]. Piezoelectric actuators are as such ideal for high resolution positioning applications. As piezoelectric actuators can produce large forces, provide frictionless motion, and the resolution is only limited by instrumentation noise, they are ideal for high bandwidth, high-resolution positioning [5]. Highly efficient and inexpensive sensors at nanometer scale such as Piezoresistive, optical, capacitive, thermal and inductive are widely used [5,6]. In this paper, piezoelectric sensor is used due its high sensitivity and resolution to measure displacement.

The model is derived for the single degree-of-freedom lateral positioning platform as illustrated in figure 2. The force developed by a piezoelectric actuator displaces the central platform. The flexures represent the stiffness introduced by guiding flexures and mechanical linkages that are often present between the actuator and platform [7-9]. The actuator generates a force which causes the platform to displace laterally. The force sensor measures actuator load while the position sensor measures platform displacement.

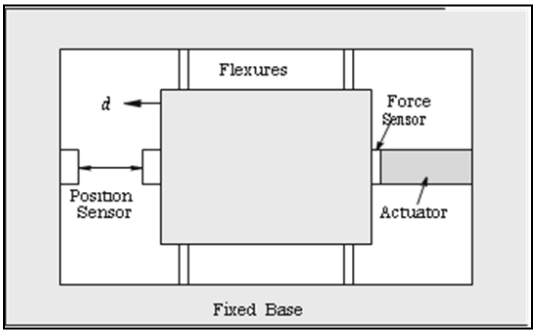

Figure 2 mechanical schematic of Nanopositioning system

The mass spring damper equivalent of a single axis nanopositioner is shown in Figure 3. The developed actuator force F_a results in a load force F_s and platform displacement d. The stiffness and damping coefficient of the flexures and actuator are denoted k_f, c_f, and k_a, c_a respectively [9-11].

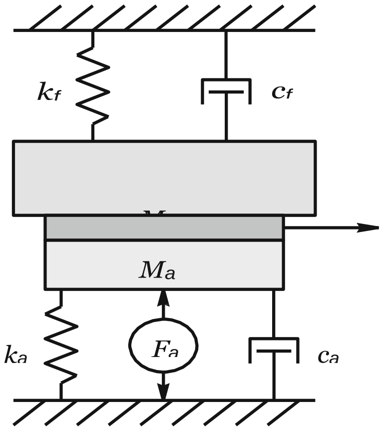

Figure. 3 Mechanical diagram of a single-degree-of-freedom nanopositioning stage

F_S is the measured force acting between the actuator and platform mass in the vertical direction. The dynamics of the suspended platform governed by Newton's second law is given as

$$(M_a + M_p)\ddot{d} = F_a - k_a d - k_{fd} - c_a\dot{d} - c_f\dot{d} \quad (1)$$

where M_a and M_p are the effective mass of the actuator and mass of the platform. As the actuator and flexure are mechanically in parallel with the suspended platform, their masses, stiffness and damping coefficients can be grouped together as

$$M = M_a + M_p \quad (2)$$

$$k = k_a + k_f \quad (3)$$

$$c = c_a + c_f \quad (4)$$

The equation of motion is then

$$F_a = M\ddot{d} + c\dot{d} + kd \quad (5)$$

Transfer function of output actuator displacement and input applied voltage is given as

$$\frac{d}{F_a} = \frac{1}{Ms^2 + cs + k} \tag{6}$$

Including the actuator gain, the transfer function from applied voltage to displacement can be written

$$G_{dva} = \frac{d}{V_a} = \frac{1}{Ms^2 + cs + k} \tag{7}$$

The load force F_s is also of interest, this can be related to the actuator force F_a by applying Newton's second law to the actuator mass.

$$M_a\ddot{d} = F_a - K_a d + c_a\dot{d} - F_s \tag{8}$$

The transfer function between the applied force F_a and measured force F_s

$$\frac{F_s}{F_a} = 1 - (M_a S^2 + C_a S + K_a)\frac{d}{F_a} = \frac{(M_a s^2 + C_a s + K_f)}{Ms^2 + Cs + K} \tag{9}$$

Now, including the actuator and sensor gains g_a and g_s, the system transfer function from the applied voltage to measured voltage can be found

$$G_{v_s v_a} = \frac{v_s}{v_a} = \frac{g_a g_s(M_p s^2 + C_a s + K_f)}{Ms^2 + Cs + K} \tag{10}$$

The two system transfer functions G_{dva} and $G_{v_s v_a}$ will be used in the following sections to simulate the performance of feedback control systems. As both of these transfer functions have the same input and poles, it is convenient to define a single-input two-output system that consists both of these transfer functions.

3. DYNAMICS OF OPEN LOOP SYSTEM

Considering the values of the system parameters given in table 1 [7], the transfer function of output actuator displacement and input applied voltage is given as

$$G_{dva} = \frac{7.5}{0.102\,S^2 + 200s + 1.75 \times 10^8} \tag{11}$$

The transfer function of output system voltage V_s and input actuator voltage V_a is given as

$$G_{v_s v_a} = \frac{V_s}{V_a} = \frac{(0.142S^2 + 142.5S + 71.25 \times 10^6)}{0.1025S^2 + 200S + 175 \times 10^8} \tag{12}$$

Table 1: Practical Assumption Values of System Parameter

Parameters	Symbol	Value
Platform mass	M_p	100 g
Actuator mass	M_a	2g
Actuator area	A	5×5mm
Actuator length	L	10mm
Young's modulus	C^E	50GPa
Charge constant	d_{33}	300×10^{-12} C/N
Actuator stiffness	K_a	12500 N/μm
Flexure stiffness	k_f	5000 N/μm
Actuator layers	N	200
Actuator damping	C_a	100N/ms^{-1}
Flexure damping	C_f	100N/ms^{-1}

The open loop time and frequency response of nanopositioning system is given in figure 4 and 5 respectively.

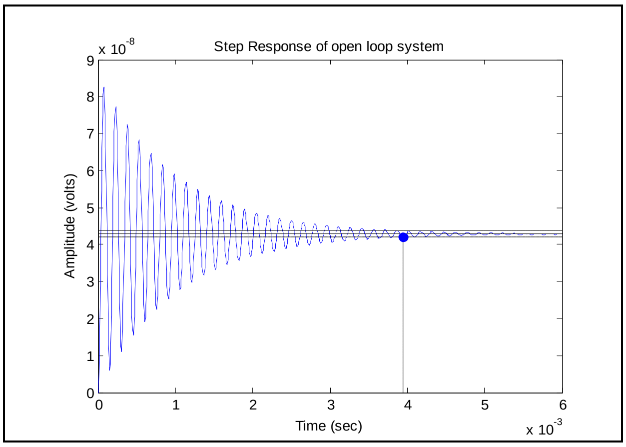

Figure 4 Step Response of the open loop system

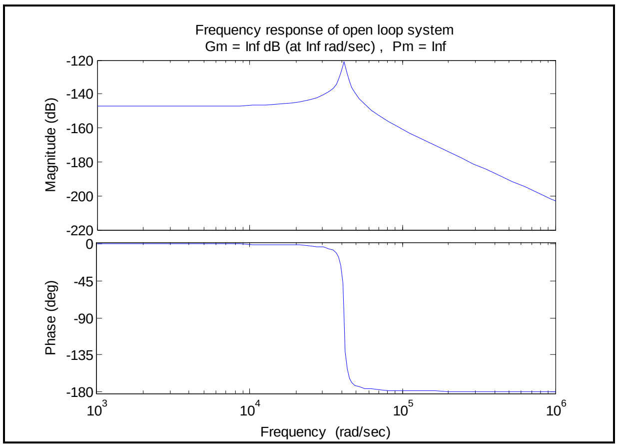

Figure 5 Frequency Response of the open loop system

The analysis of time and frequency response of open loop nanopositioning system depicts that it has very high value of peak overshoot, very oscillatory behaviour and poor stability margins. These characteristics must be improved before these are used for a particular application of nanopositioning. These characteristics can be improved by using different control techniques.

4. CONTROL OF NANOPOSITIONING SYSTEM

In closed loop system, a part of actual output of the system is feedback to the input signal where it is compared with reference input (desired output of the system) signal using comparator. The resulting error signal is applied to the controller. Controller depending upon the control strategy, controls the manipulated variable so that there is zero deviation between controlled output and desired output. Block diagram of the closed loop nanopositioning system is given in figure 6.

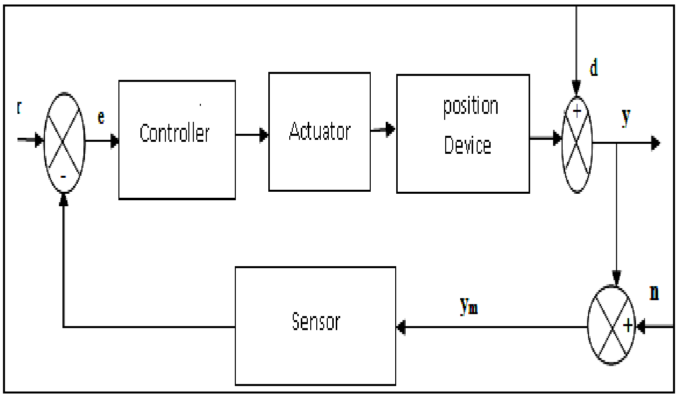

Figure 6 Block Diagram of Closed loop Nanopositioning System

In fig 5, r is the tracking - reference signal (desired output), d is the mechanical disturbances, n represents the sensor noise, y_m is the noisy measurement signal and K is the transfer function of controller [5]. The feedback control system can use proportional controller, proportional integral (PI) or proportional Integral - Integral (PII) controller to make signal y tracks the reference signal r. These controllers provide high gain at low frequencies and greatly reduce the effect of hysteresis and creep non-linearity [17].

5. TRACKING CONTROL

It concerned with identification of motion trajectories commonly used in industrial application along with the challenges in optimal path planning to meet the nanoscale motion control objective and achieve precise positioning and maximum throughput simultaneously. A positioning device utilizing piezoelectric actuators typically exhibits lightly damped vibration modes [12]. This is a disadvantage, as it limits the usable bandwidth because reference signals with high frequency components will excite the vibration modes, prohibiting accurate positioning. It also makes the device susceptible to environmental vibration disturbances, such as sound and floor vibrations [13-14]. In order to control lightly damped vibration modes in active structures, several control schemes that introduce damping have been developed. In this paper the reference signal for the tracking control is sinusoidal signal. The input signal actuator voltage applied to the system is assumed to sinusoidal which is given as

$$V_a(t)=0.5\sin t \qquad (13)$$

Input signal applied to the actuator is plotted with the system output response which is following the same path of the applied input. Due to some non linearities such as hysteresis and mechanical vibration system cannot be able to trace the same path as the input i.e shown in the figure 7.

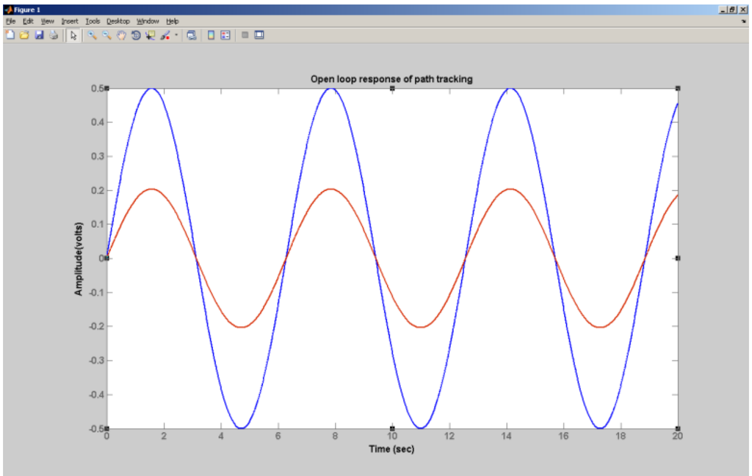

Figure 7 Path tracking of open loop nanopositioning system

6. PATH TRACKING CONTROL SCHEME

In order to obtain the path tracking, two types of control strategies, PI and PII, are used. The output response of the system must follow the same path as the applied signal. Use of PI and PII control strategies makes the response of the system much closer to the desired path.

6.1 Proportional P Controller

A proportional control system is a type of linear feedback control system in which controller output is proportional to the error signal, which is the difference between the set point and the process variable. This can be mathematically expressed as

$$K_{pout}(t) = K_p\, e(t) \qquad (14)$$

P controller reduces the value of time constant and makes the system response faster but it produces offset or steady state error [13-16]. The response of closed loop nanopositioning system using P controller is shown in figure 8.

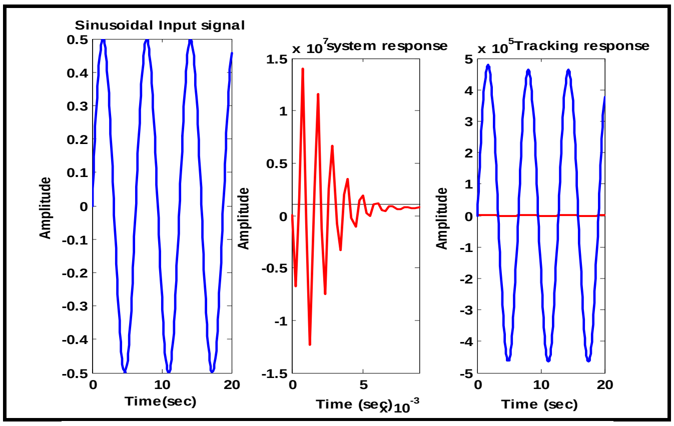

Figure 8 Closed loop response of system using P controller

The analysis of closed loop nanopositioning system using proportional controller shows that addition of proportional controller in nanopositioning system does not improve/change characteristics of the system.

6.2 Proportional Integral PI Controller

Feedback system using composite proportional integral controller is popular technique for the control of commercial nanopositioning devices. Closed loop stability can be improved by using PI controller which has transfer function

$$K_{Iout}(t) = K_p\, e(t) + K_i \int_0^t e(t)\,dt$$

$$K(s) = K_p + K_i s \qquad (15)$$

Where K_p and K_i are the gain of proportional and integral controller respectively.

The PI controller increases the speed of the response and eliminates the steady state error. It eliminates forced oscillations and steady state error resulting in operation of on-off controller and P controller respectively. PI controller has no maximum overshoot and high settling time [16]. The response of closed loop nanopositioning system using PI controller for tracking of sinusoidal input is shown in figure 9.

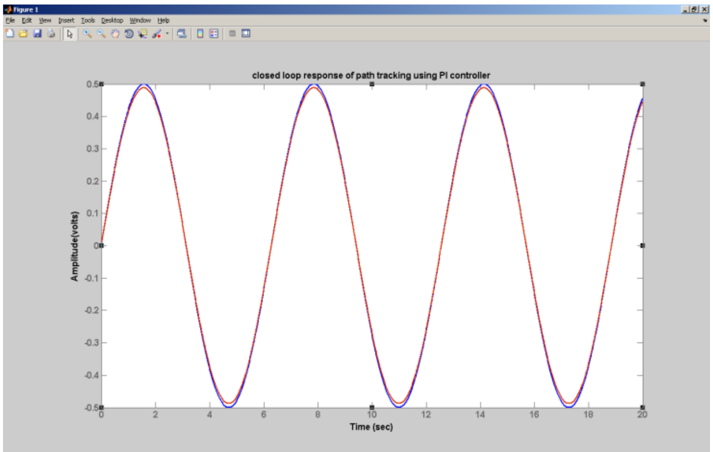

Figure 9 Path tracking of nanopositioning system using PI-Controller

The response of the system has been analysed for different values of proportional and integral controller gain. The performance analysis of closed loop nanopositioning system depicts that introduction of integral action along-with P controller in nanopositioning system improve the tracking performance drastically as compared to the P controller. But it requires very high value of proportional gain. The solution of this problem is to use PII controller.

6.3 Proportional Double Integral PII Controller

The performance improvement of the nanopositioning system can be further achieved by using PII controller [14]. Generally the traditional control design approach consists of varying the controller's transfer function until a desired closed loop performance is achieved. The tracking response of the closed loop nanopositioning system using PII controller with transfer function given by equation 16 is plotted in figure 10.

$$K_{IIout}(s) = \frac{K_p s^2 + K_{i1} s + K_{i2}}{s^2} \qquad (16)$$

Where K_{i1} and K_{i2} are the gains of first and second integral actions.

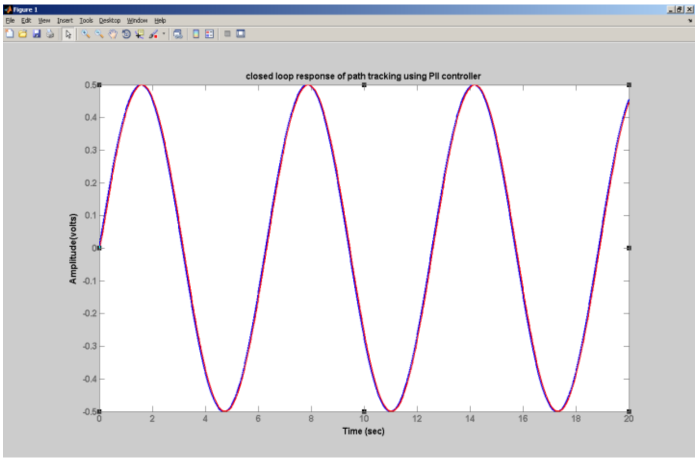

Figure 10 Closed loop path tracking performance of nanopositioning system using PII-Controller

It has been observed that rise time, settling time and maximum overshoot of the system considerably decreases with the increase in feedback gain. From the analysis of figure 10, it can be observed that path tracking performance of nanopositioning system considerably improved by using PII controller.

The analysis of figure 9 and 10 depicts that by using PI and PII controller the tracking control of nanopositioning system can be obtained with zero or approximate zero error.

7. CONCLUSIONS

In this paper a nanopositioning system consisting of piezoelectric as actuator and sensor has been identified and modeled as second order system. The open loop time and frequency responses have been analysed. Path tracking response of open loop system shows that shows that different types of non linearities such as hysteresis, creep and mechanical vibration exhibits in the system that make the nanopositioning system unable to follow the required path. Control strategies such as P, PI and PII controllers are used to overcome the problem. From the analysis of closed loop response of path tracking, it is concluded that PI controller is able to give response closer to the desired response and reduce the non linearities occurring in the system but it require higher value of the controller gain (k_i) and also setting time of the system also increases. Desired response is obtained by using PII controller with less value of controller gain and the system approaches the desired path very quickly.

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