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Design and Simulation of PID controller of nanopositioner for minimum integral of error

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***Abstract* — "NANOTECHNOLOGY is the design, characterization, production and applications of structures, devices and systems by controlling shapes and size at nanometer scale." One of the most important requirement of nanotechnology is precision control and manipulation of devices and materials at nanoscale i.e. nanopositioning. Nanopositioners are precision mechatronic system designed to move objects over a small range with a resolution down to a fraction of an atomic diameter. In particular, desired specifications of any nanopositioners are fast response with no or very little overshoot, large travel range with very high resolution, extremely high precision and high bandwidth. This paper presents design and identification of nanopositioning device consisting of flexure stage, piezoelectric actuator and displacement laser sensor. Open loop behavior of the nanopositioning device on the basis of time and frequency responses is studied. To improve the system characteristics feedback controllers are used. The key of the controller is to design a system with good dynamic characteristics as well as to maintain the desired stability margins. Despite continuous advancement in control theory, Proportional Integral Derivative (PID) controller is the most popular technique to control any process. To provide consistent, reliable and safe solution to the industrial control problems work, in this paper, Proportional (P), proportional- Integral (PI) and PID controllers are designed to minimize integral of errors. System performances for the desired parameters in closed loop are investigated. Comparative analysis of different controllers on the basis of time and frequency response is given. Simulation of results for the performance analysis is carried out in MATLAB.**

***Keywords*— Nanopositioning, Piezo-actuators, closed loop system, controller, Integral of errors.**

I. INTRODUCTION

Nanopositioners are important device of a huge family of SPMs that has emerged since the invention of the Scanning Tunneling Microscope (STM) and atomic force microscope (AFM). To achieve very high resolution a large number of nanopositioning device geometries have been proposed [5-9]. To require nanoscale precision, flexure based nanopositioning stage driven by stack piezoelectric actuators (PAs) are widely used. Flexure based mechanism eliminates back-lash, friction and lubricant requirement for the device and provide precise and repeatable motions. Use of piezoelectric actuators provides high stiffness, mechanical simplicity, compact size and effectively infinite resolution [9-12]. In general a nanopositioning device comprised of flexure stage, an evaluation stage, a piezo actuator, sensor and control system. Typically, nanopositioning stage is actuated by an assembly of piezoelectric stacks and voltage amplifier. This assembly is placed in the slot of the flexure stage. The amplified output of displacement sensor (laser) after proper control action is applied across the piezo stack which leads to its deformation and imparting motion to the flexure stage and hence to the sample. Schematic block diagram of closed loop nanopositioning system is shown in figure 1, where Piezo- actuator, flexure stage, evaluation stage and sensor represents the nanopositioning system.

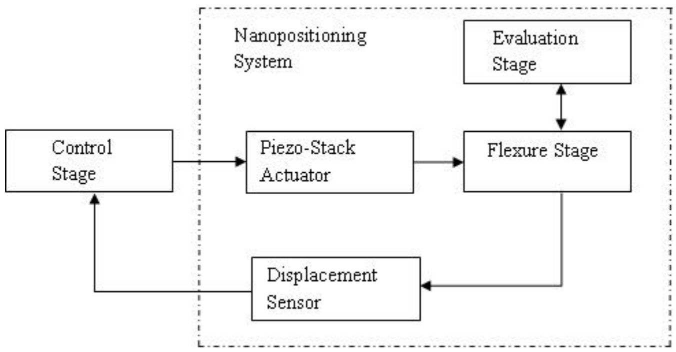

Figure 1. Block diagram of closed loop Nanopositioning System

II. DYNAMIC CHARACTERISTICS OF NANOPOSITIONING SYSTEM

Nanopositioning system described above is modeled when it operates in the linear region of its characteristics. The piezo amplifier can produce output voltage of 0-75 V. Piezoelectric actuator is driven by step input of 4.25 volts. Device is modeled using its response in time domain. Actually the relationship between the applied voltage u and resulted displacement x (transfer function) is nonlinear mainly due to the hysteresis non-linearity in the PAs. But to design a controller, a second order linear dynamics of the system similar to mass- spring damper system can be assumed by ignoring the effect of hysteresis. The presented model adequately represents the dynamics of the system which can be approximated by the linear second order transfer function given as [13]

$$G(s) = \frac{X(s)}{U(s)} = \frac{9.055 \times 10^6}{s^2 + 229.8\, s + 5.11 \times 10^5} \qquad (1)$$

Open loop analysis of the system involves finding poles and zero location in terms of system parameters and investigating the controllability and observability of the system. The locations of poles and zeros of open loop system can be found by open loop transfer function of the system. Poles are roots of denominator polynomial and zeros are the roots of numerator polynomial. Poles (eigenvalues) of open loop system are symmetric about imaginary axis consisting of pair of complex conjugate values, (-1.15×102±7.06×102i). As seen both eigenvalues have negative real part, which implying that system is asymptotically stable from the stability criteria. Damping ratio of 0.16 gives highly oscillatory response with natural frequency of 715.47 rad./sec. DC gain of the system is 17.72. The time and frequency response of the open loop nanopositioning system is given by figure 2 and 3 respectively.

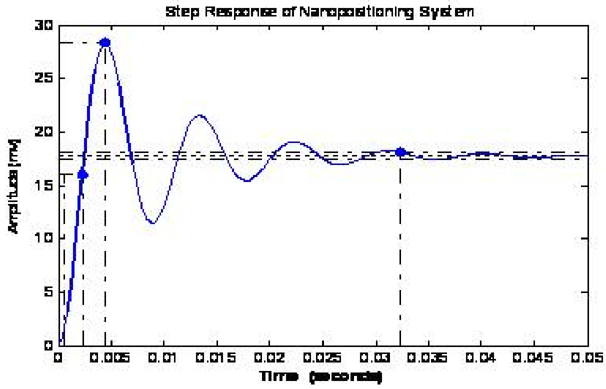

Figure 2. Time response of open loop Nanopositioning Device

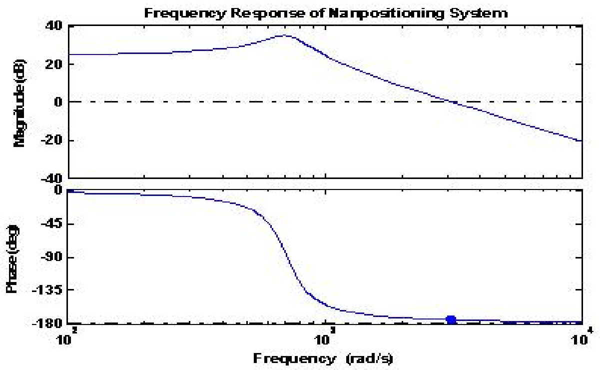

Figure 3. Frequency response of open loop Nanopositioning Device

Time response analysis gives the rise time of 1.7 msec, settling time of 0.0323 seconds and overshoot of 59.90 which is very large and must be avoided by applying suitable control techniques. It can be seen that speed of the system i.e. settling time of the transient response is governed by the dominant poles of the system. By analyzing the frequency response, it has been observed that open loop system has phase margin of 4.5 degree at gain crossover frequency of 3.09×103 rad/sec and infinite gain margin.

III. STATE SPACE ANALYSIS OF NANOPOSITIONER

Open loop system using State space representation can be described by state equation and output equation [14] given as

$\dot{x} = Ax + Bu$ State equation (2)

$$y = Cx + Du \qquad \text{output equation} \qquad (3)$$

Where x is state vector of the system
u is control signal, y is output signal
A is n×n state matrix (n is the number of states or order of system)
B is n×1 input matrix
C is 1×n output matrix
D is direct transmission matrix (scalar)

A. Controllability

A system is said to be controllable if it is possible by means of input vector u(t), to take a system from any initial state x(t0) to any final state x(tf) in a finite time (tf - t0) where t0⩽ t⩽ tf. For a completely controllable system every state must be controllable [12].

Based on controllability matrix Ct, a system given by equations (2) and (3) is said to be completely controllable if and only if the rank of controllability matrix Ct is equals to the order of system [14,15].

$$Ct = [B \vdots AB \vdots \cdots \ldots\ldots\ldots\ldots A^{n-1}B] \qquad (4)$$

A system is said to be stabilizable if matrices A and B are controllable. In the present case the rank of controllability matrix is 2 and hence system is completely state controllable.

B. Observability

An unforced system (input vector u(t) = 0) is said to be completely observable if any initial state x(t0) can be determined by the observation of output y(t) over a finite interval t0 ⩽ t ⩽ t1. Sometimes all state variables are not accessible for direct measurement, in such situations the concept of observability is very useful to reconstruct immeasurable state variables form the measurable variables in a very short period of time.

Based upon observability matrix O_t, a system described by state space equations (3) and (4) is said to be completely observable if and only if the rank of observability test matrix O_t is equals to the order of system.

$$Ot = [C^T \vdots A^TC^T \vdots (A^T)^2 C^T \vdots \cdots \ldots (A^T)^{n-1} C^T] \qquad (5)$$

A system is detectable if matrices A and C are observable. For the system given by equation (1), the rank of observability matrix is 2 which is equal to the order of system hence from the observability test theorem the system is completely observable.

IV. CONTROLLER DESIGN

The primary objective of the control design is to achieve precise tracking of arbitrary input signals with high bandwidth in spite of external disturbance. The feedback laws should be design so that it provides control signal that is within actuator saturation limits. Both feedback and Feedforward controls are important for achieving precise positioning with high resolution. The most popular technique for the control of commercial nanopositioning system is the sensor based feedback using an integral or proportional integral control. These controllers are simple, robust to modeling error and effectively reduce the piezoelectric nonlinearities because of having high loop gain at low frequencies [16,18]. In the applications where high performance and accuracy are not critical constitutive, nonlinearities of piezoelectric nanopositioning stage and hysteresis can be compensated by standard Proportional Integral (PI) or Proportional Integral-derivative (PID) controllers.

Different types of control approaches can be used to improve the positioning performance of nanopositioning devices. Different applications may require different specifications. Generally, the desired specifications for the time response include small rise time and settling time, zero steady state error, zero or very small overshoot (not more than 25%) and no oscillations. For stability requirements, phase margin (PM) and gain margin (GM) must be positive.

In closed loop system a part of actual output of the system is feedback to the input where it is compared with set point or reference signal. The error signal (difference between actual output and reference input signal) is applied to the controller.

Controller controls the manipulated variable so that there is zero deviation between actual output and desired output y. The feedback control system can use Proportional P controller, Proportional integral (PI) or Proportional Integral - Integral (PII) controller or Proportional- Integral –Derivative (PID) to minimize control error e so that actual output y tracks the reference signal r. Fast speed, increases in bandwidth, sub-nanometer resolution and reduction of effects of nonlinearity are the prime objectives of feedback system.

PID controller is the most widely used controller to control many industrial or non industrial processes because of simple structure and satisfactory performance [13]. To obtain desired performance parameters, PID controller is tuned. The values of the tuning parameters depend upon the dynamics characteristics of the device and the desired closed loop specifications. Tuning of a controller is the adjustment of its control parameters such as proportional gain Kp or band for proportional controller, integral gain Ki or reset time (integral time constant) Ti in integral controller and derivative gain Kd or rate (derivative time constant) Td in case of derivative controller. To tune PID controller, all these three parameters are to be adjusted to obtain desired performance specifications of the system [13,14]. PID controller behaves like a PI controller at low frequencies and like a PD (proportional Derivative) controller at high frequencies. So PID controller is most suitable for mid range frequencies where it behaves both as PI and PD controller.

In the time domain the output u(t) of the controller can be written as:

$$u(t) = K_p\left[E(t) + \frac{1}{T_i}\int_0^t E(t)\,dt + T_d\frac{dE(t)}{dt}\right] \quad (6)$$

Based on Integral error criteria, controller tuning relation optimizes the closed loop response of a simple process model for disturbance rejection and set point change. The optimum setting minimizes the integral error criteria and utilizes the entire response of the process. The integral of the square (ISE) criteria penalizes the large error and Integral of the time weighted error absolute (ITAE) criteria penalizes the error that persist for long period of time. In general ITAE ia also a preferred criteria because it results in most conservative controller design setting. For the suppression of small error, integral of the absolute value of the error (IAE) is better than ISE.

V. Simulation and Analysis of Controllers

The design objective is to determine a controller Gc(s) to obtain good set point response and system's stability margins In this paper, to minimize integral errors such as IAE, ISE, ITAE and ITSE, P, PI and PID controllers are designed using MATLAB SISO design toolbox. The proportional controller gain for all error criterions is same and the time and frequency response performance parameters for proportional controller are given in table 1.

Table 1. Performance characteristics of system using proportional controller

Integral error	Rise time (sec.)	Settling time (sec.)	Maximum overshoot	Gain margin (db)	Phase margin
IAE = ISE	0.000357	0.0335	88.7%	8	6.47

As seen from the table 1, the use of P controller improved the transient response characteristics and stability characteristics. There is a drastic improvernent in the rise time of the system response from 0.001666 to 0.000357 sec. but this controller also increases the value of maximum overshoot. To decrease maximum overshoot, an integral term can be attached to the proportional controller. The performance parameters of PI controller for different error criterion are given in table 2.

Table 2. Performance characteristics of system using PI controller

Integral error	Rise time (sec.)	Settling time (sec.)	Maximum overshoot (%)	Peak Gain (db)	Phase margin (degree)
IAE	0.000383	0.0666	83	27.5	3.28
ISE	0.0017	0.0562	14.6	13.5	10.2
ITAE	0.0628	1.22	0	5.48	38.3
ITSE	0.000383	0.0666	83	27.5	3.28

Analysis of table 2 depicts that PI controller improves the maximum overshoot but at the cost of increase in rise time. Moreover the response of closed loop nanopositioning system for IAE and ITSE are same. The use of PID controller improves the system performance effectively. The time and frequency response of PID controller is shown in figure 4. The analysis of these responses of the nanopositioning system using PID controller to minimize all errors is tabulated in table 3. Again the PID controller transfer function and performance of system is same for all error criterions.

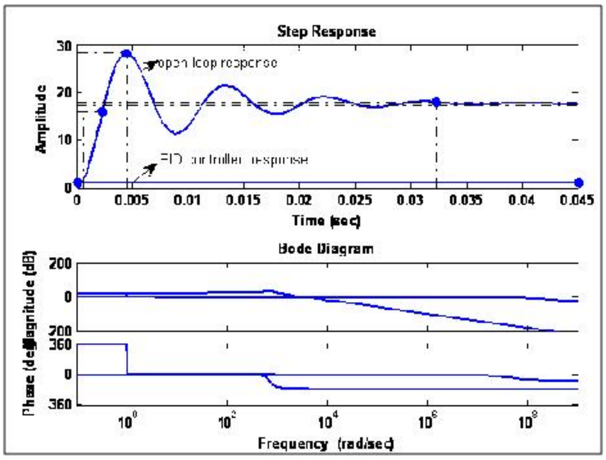

Figure 4. Time and frequency response of nanopositioning system

Table 3. Performance characteristics of nanopositioning system using PID controller

Integral error	Rise time (sec.)	Settling time (sec.)	Maximum overshoot (%)	Gain margin (db)	Phase margin (degree)
IAE	4.86×10^{-8}	2.39×10^{-9}	0	21.1	80

VI. CONCLUSIONS

The open loop response of the system shows that it has very slow response with high value of maximum overshoot. The transient response characteristics and stability margins of the system have been improved using different controller on the basis of minimization of the integral of error. Use of proportional controller hardly improves the system performance. PI controller for IAE gives good results regarding transient response parameters. For ITAE, PI controller totally eliminates the maximum overshoot. Drastic improvement in the system performance has been achieved using PID controller. This controller gives rise time of 4.46×10-8sec. as compared to 0.00166 sec. of open loop system and totally eliminates the maximum overshoot.

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