Identification and Iterative Learning Control of Piezoelectric Actuator Based Nanopositioning System

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Abstract— **This paper presents the identification of piezoelectric actuated nanopositioning system. The open loop characteristics of the system are analyzed on the basis of time and frequency response and depicts that the open loop characteristics of the system are not satisfactory and require some control technique to improve system characteristics. Through the years, several control techniques have been studied to improve the performance of the system. The desired system should have short settling time and must have the ability to reject all disturbances. To achieve these objectives, the present paper design Iterative Learning Control (ILC) for the nanopositioning system to reject disturbance which are periodic in nature. System performances for the desired parameters using ILC are investigated and analyzed. The whole work of simulation and implementation of the ILC is done by using MATLAB/SIMULINK software.**

Keywords- Nanotechnology, Nanopositioner, Piezoelectric actuator, LVDT, Iterative Learning Control.

I. Introduction

Today the demands of design and manufacture of miniature devices have been increasing in both research laboratories and industries. 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. Nanoscience is the study of phenomena and manipulation of matter at nanometer or sub-nanometer dimensions. Nanotechnology 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 [1,2]. 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. It is widely recognized that one of the key requirement of nanotechnology is the nanopositioning [3,4].

Nanopositioning is the precision control and manipulation of devices and materials at nanoscale with incredible accuracy. Nanopositioners are precise mechatronics systems designed not only to move or position a probe, part, tool, sample, or device at some desired position with nanometer accuracy and repeatability but also to resolve adjacent positions that are separated by less than a nanometer. Nanotechnology is supposed to become the key technology of 21st century [3,4]. The key of nanotechnology is the nanopositioning. Applications of nanopositioning include the alignment of optical fibre, optical beam pointing, positioning in scanning probe microscopes (SPMs) and nanofabrication [5-8]. Manipulation and interrogation at nanoscale with the scanning probe microscope (SPM) necessitate positioning system with nano scale resolution. For surface interrogation and modification, nanopositioning is needed to scan the probe over a sample during surface imaging and to control the interaction between probe and sample surface etc. In general, nanopositioning is the key enabling technology for any high throughput scanning probe technique [9]. A nanopositioning device consists of a sensor to measure the position of the nanopositioning stage 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.

Iterative Learning Control (ILC) is a technique used to achieve a higher accuracy of the systems that carry out with a repetitive task. Among the recent control methods, ILC methods grab nowadays the attention of many researchers for various control applications. A feed-forward can be used to compensate the repeated disturbance. In Iterative Learning Control, tracking error signal is used to calculate the feed-forward signal. When feed-forward signal is used in the system, next time the error is decreased. This procedure can be repeated in number of times up to error can reach to the minimum value. It also improves its ability to reject a repeated disturbance signal [10,11].

There are number of ILC algorithms have been developed to provide accurate trajectory tracking, faster convergence of error. The iterative learning control (ILC) was introduced by Uchiyama [12] used the concept of learning control which was not widely spread as it was written in Japanese language However, the extensive work done by Arimoto in mid 1980's laid down the foundation of learning control theory [13]. As time span, it becomes standard notion for the research area [14].

This paper is organised as follows: section 2 covers the identification of nanopositioning system. The simulation implementation of open loop behaviour is presented in section 3. Section 4 is devoted to the design of Iterative learning control. It consists of a control structure and learning convergence formula. Section 5 is the implementation of the iterative learning control to nanopositioning system, and Section 6 draws the conclusion and result.

II. NANOPOSITIONING SYSTEM

Nanopositioners are the essential requirement in virtually all applications of nanotechnology and further research in the SPM based research area depends on the availability of highly precise nanopositioning devices [3]. The main issues for the nanoscale precision positioning system are to design and manipulate the positioning system with extremely high resolution, bandwidth, accuracy and stability. To achieve very high resolution, high bandwidth, and fast time response, a large number of nanopositioning device geometries have been proposed [15-18].

A Nanopositioning system is an assembly of precise detection system, solid state smart actuators driven by state of art modern control systems and monolithic motion guide stage (flexure and evaluation stages). Block diagram of typical nanopositioning system is shown in figure 1. The positioning bandwidth of the nanopositioner is the combined effect of nanopositioner itself, load of the nanopositioner, sensor, actuators and controllers used.

In order to realize precise positioning at sub nanometer resolution, all these elements must be carefully designed, analyzed and optimized.

An important issue for the design of controller is the availability of sensor and actuators for the nanopositioning system. Review of some important sensors and actuators used for nanopositioning system ar*e described by Devasia et al [3*].

Speed and positioning accuracy of nanopositioning systems depend upon the position sensing mechanism. Sensors based on techniques such as Inductive, piezo-resistive, capacitive and optical sensors are suitable for nanopositioning applications [3].

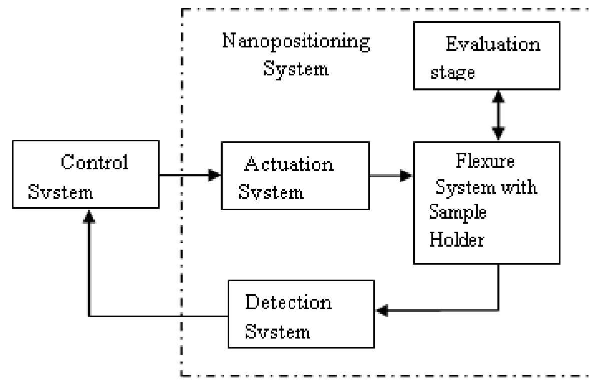

Figure 1. Block Diagram of Nanopositioning System

A. *Nanopositioning stage*

In all applications of nanotechnology, nanopositioning i.e precise positioning at nanoscale resolution plays an important role. A true nanopositioning device provides frictionless motion, virtually instantaneous response, high linearity and stiffness, subnanometer resolution and trajectory control in the nanometer scale. The nanopositioning stage can be single axis, 2 axes, or 3 axes linear or rotational type or combination of two [19]. The mechanical design/dynamics of the nanopositioning stage provides fundamental limitation on the performance achieved of any nanopositioning system. For highly accurate and high speed nanoscale positioning applications, recently, nanopositioning system consisting of flexure guided mechanism are emerged. These types of nanopositioners provide repeatable, reliable and smooth operation for precise and accurate nanoscale positioning. High speed scanning, long range, higher dominant resonant frequency, less cross coupling of different axes of motion and less non linearities in the actuation directions are some more key advantages of flexure guided nanopositioners [20].

B. *Sensor for Nanopositioning System*

Sensors are used for recognition, identification and quantification of any physical quantity. In typical Nanopositioning applications, the displacement of the flexure stage is usually in the order of nanometer and sub nano meter range. Speed, positioning accuracy of motion and reliability of the nanopositioning systems depend on how the extremely low level output voltage from the sensor is captured, conditioned and presented to the position control algorithm. To meet all these requirements, advancement of nanotechnology is enabling the development of highly efficient and inexpensive sensors at nanometer scale. For ultra-high precise positioning applications, sensors based on variety of positioning sensing techniques such as piezo-resistive, optical, capacitive, thermal and inductive are widely used. A capacitive sensor, LVDT, a position sensitive detector (PSD) can detect displacement down to subnanometer range. [3,21].

International Journal of Advances in Engineering Sciences Vol.3 (3), July, 2013 e-ISSN: 2231-0347 Print-ISSN: 2231-2013

C. Actuators for Nanopositioning System

Actuators are used to convert electrical signal generated by controllers into non electrical signal. Actuators used for nanopositioning system must have high resolution and bandwidth. Power consumption, dimensions, weight, force and displacement range under diverse working conditions of the actuators are the important design parameters to be considered during particular application of the nanopositioning system. Some of the actuators perform well for some characteristics, but not for all characteristics. Different types of the actuators utilized in nanopositioning system depend upon type of material which includes, piezoelectric, electrostatic, electromagnetic, magnetostrictive and thermal actuators [3]. The new design of nanopositioning systems is based upon the piezoelectric stack actuators and flexure mechanism that enable the decoupling of the different axes motion while keeping the mechanical structure stiff [20]. Piezoelectric actuators are undoubtedly used for nanopositioning applications because of high resolution, very high speed and compact size. Achievable positioning accuracy and bandwidth of nanopositioning system consisting of piezoelectric actuator is limited by the presence of inherent nonlinearities and dynamics of the actuator inertia, damping and stiffness. The inherent nonlinearities include input-output hysteresis, drift due to creep and induced structural vibration [20, 22-26] and limit the performance of nanopositioning system.

D. Control of Nanopositioning System

The performance of nanopositioning system is highly affected by mechanical dynamics/ design of the motion stage, inherent non-lineaarities present in the piezoelectric actuators, external disturbances and drift due to the temperature variation. Vibration effect limits the operating bandwidth of nanopositioner. Drift due to temperature and creep effect results in approximately 30% positioning error for slow and static positioning applications. Similarly hysteresis nonlinearity results in 20% positioning error. To reduce inherent nonlinearities of piezoelectric actuator and to improve nanopositioning system's performance, control plays an important role. A variety of control schemes such as Feedback and feedforward control schemes, iterative learning control etc. are used to control the nanopositioning system [3,20,22-26].

III. DYNAMIC CHARACTERISTICS OF NANAPOSITIONG SYSTEM

Device is modeled when it operates in the linear region of its characteristics. The piezo amplifier can produce output voltage of 0-75 V. A sinusoidal input voltage Va=-5+Asin(wt) volts with a frequency spanning a bandwidth of 2kHz is generated [27]. To have approximate linear response of piezoelectric actuator, the amplitude A of the input signal is chosen to be less than 50mVolts. Device is modeled by studying its frequency response over a specified bandwidth. Offset of -5V is given to operate the device about the null position. The dynamics of a given point x on the mechanical system attached to the actuator can be described as linear lumped parameter system with the infinite number of resonant frequencies. 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 Piezoelectric actuator 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 4th order transfer function given as [27]

$$G(s) = \frac{Y(s)}{V_x(s)} = \frac{96700s^2 - 1.397 \times 10^9 s + 1.034 \times 10^{13}}{s^4 + 4040s^3 + 2.71 \times 10^7 s^2 + 1.45 \times 10^{10} s + 5.527 \times 10^{13}} \quad (1)$$

This is a non- minimum phase (NMP) system consisting of one pair of complex conjugate zeros in the right half s-plane (RHP) which pose limitations on the performance specifications of the device and control of NMP system requires special attention.

Open loop poles and zero location of the system can be found by open loop transfer function of the system. The locations of poles (eigenvalues), damping ratio and natural frequency associated with the open loop system are given in table 1

Table 1 Zeros, Eigenvalues, Damping and natural Frequency of open loop nanopositioning system

Zeros	**Eigenvalue**	**Damping**	**Freq. (rad/s)**
$7.2\times10^3+7.4i\times10^3$	$-1.90\times10^3 \pm 4.50\times10^3 i$	0.389	4.88×10^3
$7.2\times10^3-7.4i\times10^3$	$-1.20\times10^2 \pm 1.52\times10^3 i$	0.0787	1.52×10^3

All eigenvalues have negative real part, which implying that system is asymptotically stable from the stability criteria. Poles and zeros of open loop system are symmetric about imaginary axis consisting of pair of complex conjugate values. The presence of complex conjugate poles indicates that the response has sine and cosine terms and the system has oscillatory response. Pair of damping ratios and natural frequency denotes two natural modes of the system. The poles farther to the left in s-plane are associated with the natural signals that decay faster than those associated with the poles closer to the imaginary axis. A pair of highly damped modes [-(1.9 ± 4.5i)×10^3] having larger value of natural frequency and dictating the control input magnitude are called short period modes. Pair of very lightly damped characteristic modes [-0.120 ± 1.52) ×10^3] with lower value of natural frequency are known as long period mode or dominant poles. The damping ratio of dominant poles is very small (0.0787) and need controllers to improve the damping ratio and hence the phase margin.

Simulated time and frequency responses of the open loop nanopositioning system are given in figure 2 and 3 respectively.

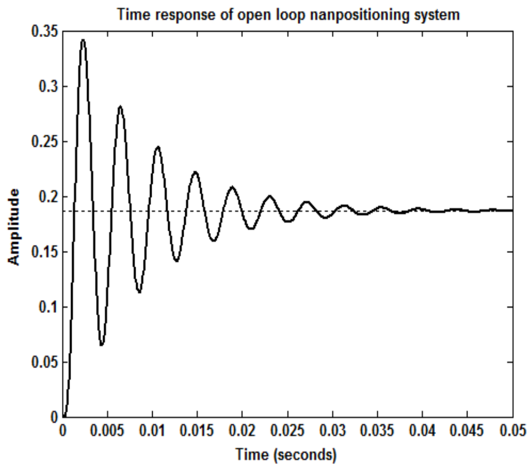

Figure 2 open-loop response of nanopositioning system to unit step actuated force

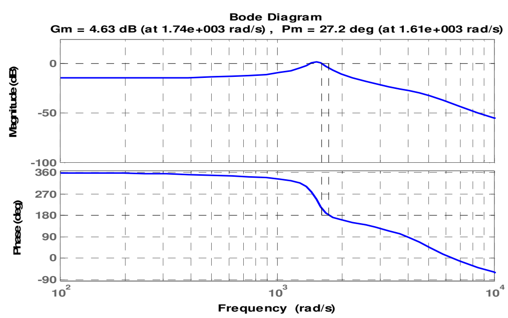

Figure 3 Simulated Frequency response of nanopositioning system

By analysing the frequency response it is observed that it gives phase margin of 27.2 degree at gain crossover frequency of 1.61×103 rad/sec and gain margin of 4.63dB (1.7) at phase crossover frequency of 1.74 × 103 rad/sec. It is found that there is very small variation in the frequency response of the system from DC signal to AC signal. The bandwidth of the system is given as 2.48kHz. Time response analysis gives Settling Time of 0.0335 seconds, rise time of 0.6599 msec. and overshoot of 83.6016 which is very large and must be avoided using proper control techniques.

IV. ITERATIVE LEARNING CONTROL

Iterative Learning Control is a control strategy to achieve a higher accuracy for systems with repetitive tasks. Often, disturbances in systems are position dependent or the system's dynamics are excited in a similar way during each trajectory. The repeated disturbance can be compensated for with a feed forward. Using Iterative Learning Control, a feed forward signal call easily be calculated from the tracking error signal. When this feed forward signal is injected, the next time the error is decreased. This procedure can be repeated several numbers till the error can no longer decrease.

A simple control law is in the form:

$$u_{j+1} = u_j + K * e_j \tag{2}$$

where u_j is the input to the plant during the j[th] repetition, e_j is the tracking error during the j[th] repetition and K is a design parameter representing operations on tracking error e_j [28].

A. *Control structure*

Iterative learning controllers can be classified in different ways. Generally, ILC structures can be classified into two major categories: embedded configurations and cascaded configurations. The block diagram shown in Figure 4 [28] represents most commonly used embedded configurations of ILC strategy. It is called as the previous cycle learning block [28]. In figure 4, $r_j(t)$ is the reference signal, $y_j(t)$ is the output of the process and $u_j(t)$ denote the control signal in time domain at the j[th] iteration. G_p and K are the transfer function of the plant and the learning control gain, respectively.

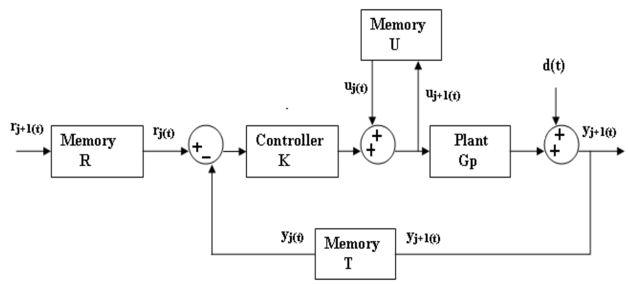

Figure 4 Block Diagram of Iterative Learning Control Strategy

The present system has as a periodic reference signal, $r_j(t)$ and hence $r_{j+1}(t) = r_j(t)$. The memory blocks used here are FIFO buffers (first in first out) with a time delay equals to the period of the every iteration. The memory blocks R, U and T in figure 4 are used to save the information of $r_j(t)$, $u_j(t)$ and $y_j(t)$ respectively. The information saved in the memory blocks is used in the next learning cycle which provides the learning characteristic of the ILC scheme.

B. *Learning convergence formula*

The ILC approach is convergent which is proved in following equations:

Let,

$$r_j(t) = G_p u_j(t) \tag{3}$$

Laplace Transform of equation (3)

$$Y_j(s) = G_p(s)U_j(s) \quad (4)$$

where $Y_j(s)$ is known as the output signal at j^{th} iteration. The tracking error, e(t), is defined as

$$e_j(t) = r(t) - y_j(t) \quad (5)$$

the discrete-time update of the control signal will be

$$u_{j+1}(t) = u_j(t) + Ke_j(t) \quad (6)$$

which is called the ILC updating law.

By choosing proper value of K, a faster tracking response is obtained. Furthermore, by converting from the time domain to the frequency domain, using Laplace transform $x(t) \rightarrow X(s)$, the learning convergence condition for ILC is derived as follows.
Taking Laplace of equation (6)

$$E_{j+1}(s) = R(s) - y_{j+1}(s) \quad (7)$$

$$= R(s) - G_p(s)U_{j+1}(s) \quad (8)$$

$$E_{j+1}(s) = R(s) - G_p(s)(U_j(s) + KE_j(s)) \quad (9)$$

$$= (1 - KG_p(s))E_j(s) \quad (10)$$

$$\frac{E_{j+1}(s)}{E_j(s)} = 1 - KG_p(s) \quad (11)$$

If the tracking error signal of the first iteration is finite, then the error becomes smaller after every iteration if and only if the following condition holds

$$\left\| \frac{E_{j+1}(s)}{E_j(s)} \right\| = \| 1 - KG_p(s) \| < 1 \quad (12)$$

where the norm $\|...\|$ is the infinity norm for all frequencies, with $\omega \varepsilon \Omega, \omega = [\omega_a, \omega_b]$ and $\omega_b > \omega_a > 0$. Ω denotes the frequency band of interest or the frequency band that matches the bandwidth of a controller [16].

V. IMPLEMENTATION OF ITERATIVE LEARNING CONTROL FOR NANOPOSITIONING SYSTEM

In this section, the iterative learning control is applied to the Nanopositioning system. The SIMULINK model of ILC compensator for Nanopositioning system is shown in figure 5. The internal model of ILC Compensator is shown in figure 6.
Gain of the proportional, integral1 and integral2 are 0.001, 450 and 100000 respectively. In Naopositioning applications to track the signal PII controller is widely used. The tracking error and disturbance rejection ability are investigated with the help of SIMULINK.

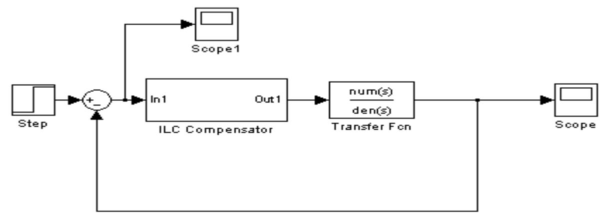

Figure 5 SIMULINK Model of Nanopositioning system using ILC Compensator

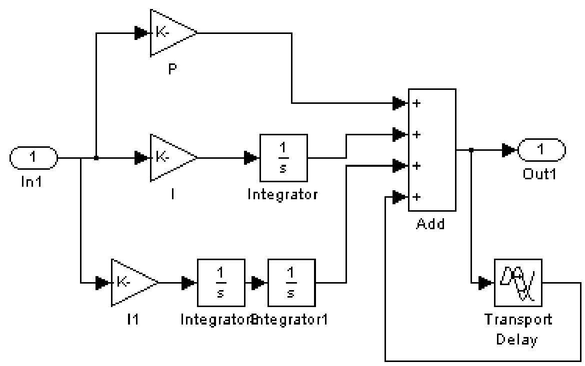

Figure 6 SIMULINK Model of ILC Compensator

A. *Tracking Error performance*

The tracked error is shown in Figure 7. It is observed that the tracking error with disturbance becomes zero within 0.14 seconds and has less overshoot.

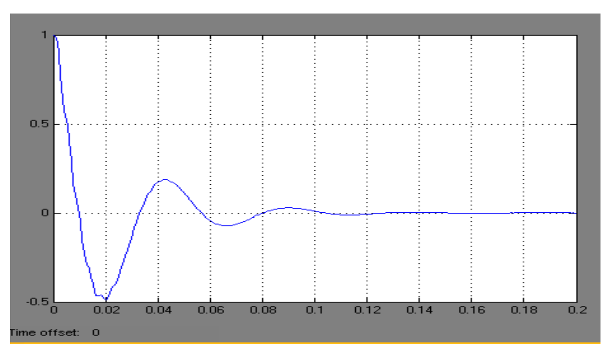

Figure 7 Tracking of errors with disturbances

B. *Disturbance Rejection Performance*

To investigate the disturbance rejection ability, It is observed from figure 8 that the disturbance becomes zero in 0.14 sec with very low value of overshoot which satisfies our design criterion.

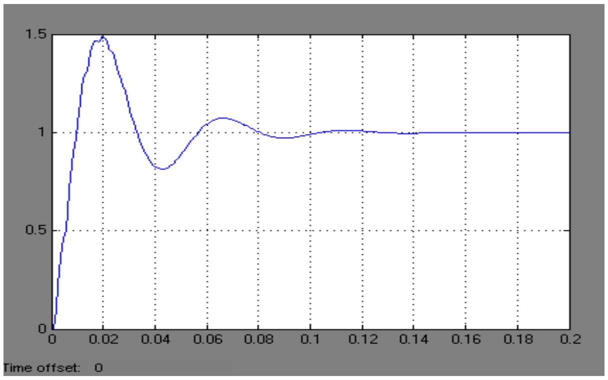

Figure 8 Disturbance rejection response of ILC Compensator for nanopositioner

VI CONCLUSION

In this paper, a nanopositioning device consisting of piezoelectric actuator, nanopositioning stage and sensor has been identified. The open loop characteristics of the system have been investigated using time and frequency responses. ILC controller has designed and implemented for controlling a nanopositioning system and it has been found that a good signal tracking has been achieved. Reduction of tracking error is very fast. Tracking disturbance rejection using ILC controller is very fast and level of maximum overshoot is also reduced to a satisfactorily level. The proposed model fulfill the aim to developed and carry the response of system using ILC controller up to a better level.

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