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Settling Time Improvement of Piezoelectric Actuated Nanopositioning System Using Fuzzy Logic Based PID Controller

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Abstract
Large travel range with very high resolution, fast response with no or very little overshoot, extremely high precision and high bandwidth are some of the desired characteristics of any nanopositioning system. This paper presents the design and identification of nanopositioning system consisting of flexure stage, piezoelectric actuator and Linear Variable Differential Transformer (LVDT) as a sensor. Time and frequency responses of open loop nanopositioning system is analysed and it has been observed that settling time taken by the nanopositioning system to reach at desired destination is very high. System performance can be improved by using different types of control schemes. This paper describes the implementation and simulation of conventional P, conventional PI,fuzzy logic based PI and Fuzzy logic based PID controllers using MATLAB environment to improve the time response characteristics of nanopositioning system. With the help of simulated results, it has been observed that substantial improvement in time response characteristics of fuzzy logic based PID controlled nanopositioning system has been achieved by reducing the settling time.

Keywords: Nanotechnology, Nanopositioning, piezoelectric actuator, nanopositioning system, PID controller, fuzzy logic controller.

INTRODUCTION

Nanotechnology is the design, characterization, production and application of structures, devices and systems by controlling shapes and size at nanometre scale that produces structures, devices, and systems with at least one novel/superior characteristic or property [1,2]. In all applications of nanotechnology,precise positioning at nanoscale resolution, plays an important role. Nanopositioning is the precision control and manipulation of devices and materials at nanoscale. Nanopositioners or nanopositioning systems are precise mechatronics systems designed not only to move or position a probe, part, tool, sample, or device at some desired position with nanometre accuracy and repeatability but also to resolve adjacent positions that are separated by less than a nanometre[3,4]. The main issues for the nanoscale/precise positioning are to design and manipulate the positioning system with extremely high resolution, bandwidth, accuracy and stability.

A nanopositioning system as shown in figure1, consists of an assembly of precise detection/sensing system, solid state smart actuators driven by a control systems and monolithic motion guided mechanism [3]. 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 nanometre resolution, all these elements must be carefully designed, analyzed and optimized. To achieve very high resolution, high bandwidth, and fast time response, a large number of nanopositioning device geometries have been proposed [4-8].

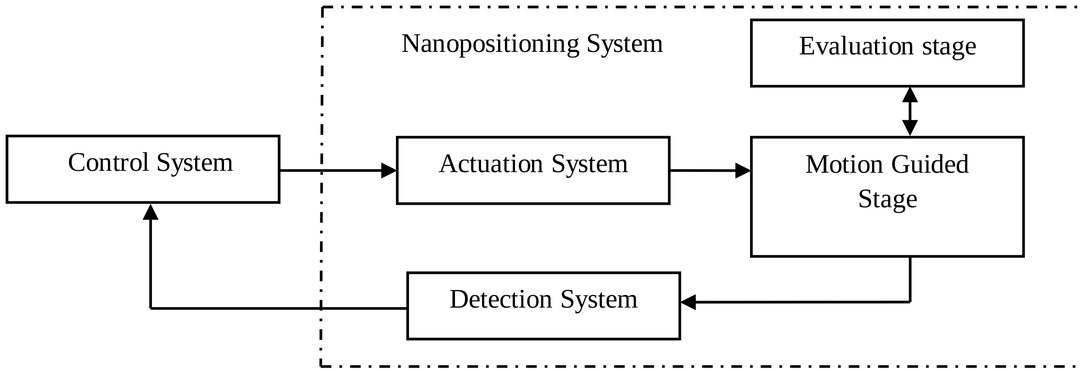

Figure 1 Nanopositioning System

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 [6]. 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 are described by Devasia et al [3,9-10].

For highly accurate and high speed nanoscale positioning applications, recently, nanopositioning system consisting of flexure guided mechanism as motion guided 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 [9,11-12].

Generally, motion guide stage or nanopositioning stage can be used to reproduce almost perfect linear or rotary motion or a combination of both. A true nanopositioning stage provides frictionless motion, virtually instantaneous response, high linearity and stiffness, subnanometre resolution and trajectory control in the nanometre scale. It can be single axis, 2 axes, or 3 axes linear or rotational type or combination of two [13-15]. The mechanical design/dynamics of the nanopositioning stage provides fundamental limitation on the performance achieved of any nanopositioning system. The achieved bandwidth is limited and can roughly be estimated equal to frequency of the dominant vibration mode of the nanopositioning stage. There is an inverse relationship between range of nanopositioning stage and bandwidth, so to achieve high bandwidth, range is usually limited [16].

Sensors for nanopositioning stage

To develop a highly precise closed loop nanopositioning system, a very high degree of displacement precision is required and hence robust sensor, accurate source of the position information and signal conditioning units are essential [3,9]. In typical nanopositioning applications, the displacement of the flexure stage is usually in the order of nanometre 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 nanometre scale. Nanotechnology enabled sensors may offer significant advantages over conventional sensors such as greater sensitivity and selectivity, lower production costs, reduced power consumption as well as improved stability because of high surface to volume ratio [17].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 [3,9,18-21].

Actuators for Nanopositioning System

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. 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 [3,9]. Depending upon type of material, different types of the actuators such as piezoelectric, electrostatic, electromagnetic, magnetostrictive and thermal actuators utilized in nanopositioning system are available [3,9, 22-24].

Controllers for Nanopositioning system

Long travel range, precision, accuracy, speed and resolution are the performance characteristics of nanopositioners. These performance characteristics are highly affected by mechanical dynamics/ design of the motion stage, inherent nonlinearities present in the piezoelectric actuators, external disturbances and drift due to the temperature variation. 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. Vibration effect limits the operating bandwidth of nanopositioner [25-27].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 and fuzzy logic controllers canbe used to control the nanopositioning system.

In a closed-loop/ feedback control scheme, the controller responds to a feedback signal from the position sensor and moves the positioner to reduce the difference between the sensed position and the desired position and hence improve the positioning accuracy. Speed and time response of nanopositioning system is determined by the closed loop bandwidth. Feedback controllers such as PID controllers are generally used due to their robustness and high low frequency gain. Integral controllers can overcome creep and hysteresis nonlinearities effectively but offer limited bandwidth. In order to achieve higher bandwidth, higher order controllers are used. State feedback controllers and H_∞ controllers demonstrate substantial improvement in positioning under the influence of hysteresis and creep.

Feedforward controllers can be used to reduce the vibration effect, creep and hysteresis nonlinearities present in the nanopositioning system because of use of piezoelectric actuators. But feedforward control scheme require perfect model of the system.Using the feedback control, the performance of the sensor determines the precision and accuracy (trueness) attainable from the nanopositioning system. During the feedback control scheme, the sensor noise will be feedback to the input and will increase the overall noise of the system, so the noise specifications of the sensors are stricter in the feedback control scheme as compared to the feedforward control scheme where sensors are used for system identification only.

Feedforward controllers cannot eliminate tracking errors due to plant uncertainty, therefore integrated feedback and feedforward controllers are used to reduce errors caused by plant uncertainties.

OPEN LOOP DYNAMICS OF NANOPOSITIONING SYSTEM

Time and frequency response of open loop nanopositioning system are shown in figure 2.

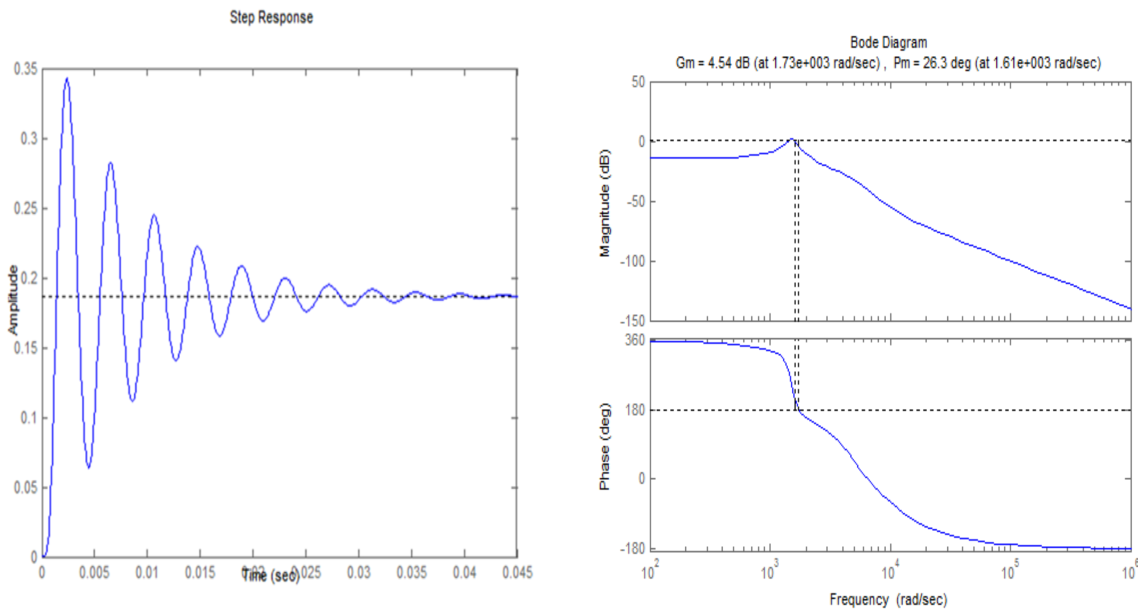

Figure 2Timeand Frequency Response of Open Loop Nanopositioning System

The frequency response of the above system depicts that the open loop system has phase margin of 26.3 degree and gain margin of 4.54 dB and time response of that system gives rise time of 0.00066sec, settling time of 0.0336sec, overshoot of 83.8% which is very large and must be reduced by using suitable control techniques.

PID control of Nanopositioning system

PID controller is the most widely used controller to control many industrial and non- industrial processes because of its simple structure and satisfactory performance. Block diagram of the closed loop nanopositioning system is given in figure 4.1 where G(s) is the transfer function of nanopositioning system consisting of piezo-electric actuator, nanopositioning stage and LVDT sensor and K(s) is the transfer function of controller.

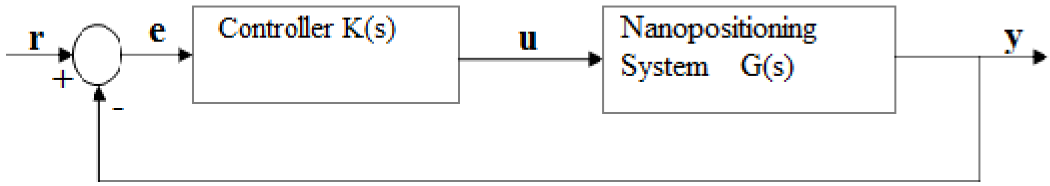

Figure 3 Closed Loop Nanopositioning System

As shown in figure 3, in the feedback or closed loop system, a part of actual output y of the system is feedback to the comparator to compare it with set point or reference signal r. The error signal e representing the difference between actual output y and reference signal r is applied to the controller. Depending upon the type of controller used, the controller computes either proportional or derivative or integral or combination of any two or all, of the error signal. For PID controller the output u is equals to the proportional gain times the magnitude of the error plus the integral gain times the integral of error plus the derivative gain times the derivative of the error. Mathematically output u(t) of the PID controller is given as

$$u(t) = K_p \left[e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d \frac{de(t)}{dt}\right]$$

and transfer function of the PID controller is given as

$$u(s) = K_p[e(s) + \frac{1}{T_i s} e(s) + sT_d\, e(s)]$$

Where K_p, T_i and T_d respectively are the proportional gain, integral time and derivative time constant of the controller. Output u(t) of the controller is sent to the system and new value of system output is obtained. This new output y will be sent back to the comparator to find new value of error signal e. The controller again computes the different parameters and sent output u to the plant. This process goes on so that there is zero deviation between actual output y and desired output r of the system.

Ziegler- Nichols (Z-N) is the most widely used method as an initial guess for the optimization problems. Its tuning depends upon the gain of proportional controller i.e. ultimate gain K_c at which loop oscillates with constant amplitude (sustained oscillations) and the period of these oscillations i.e. known as the ultimate period T_c. For some control loops, oscillations and the corresponding large overshoots for the set point changes are undesirable, therefore, more conservative method such as Modified Ziegler Nichols method is preferred. Moreover, since the output does not change instantaneously for a step input, a smoother signal is produced by taking the derivative of the output and to reduce the effect of plant input saturation due to step change in reference input, the derivative term may be preferred in the feedback path. The tuning parameters of PID controller using Z-N and modified Z-N are described in literature (28-33).The step response of nanopositioning system using PID controller with filter and PID controller with derivative action in feedback path using Z-N tuning algorithm is shown in figure 4.

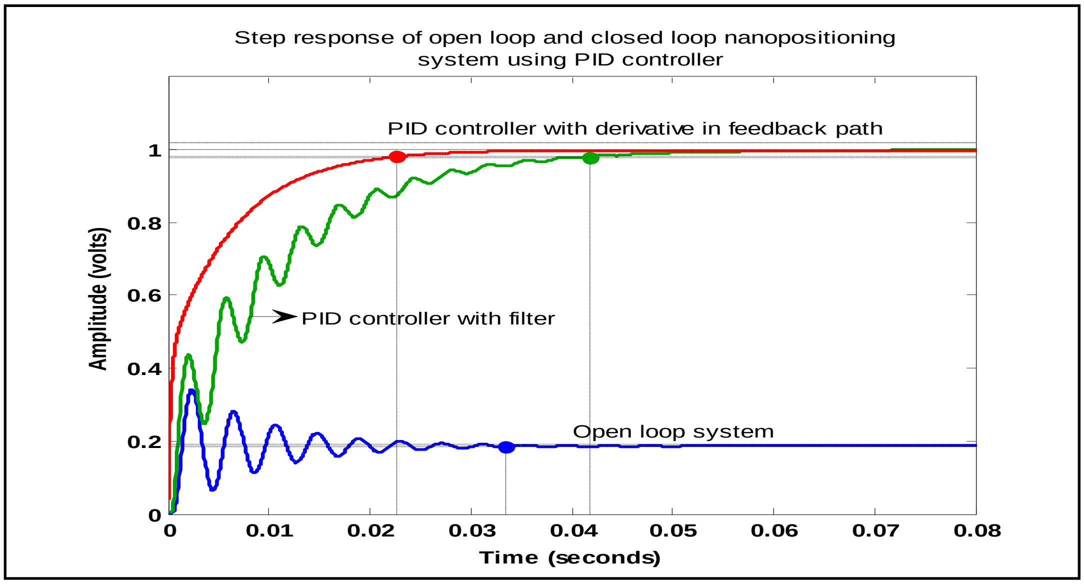

Figure 4 Closed Loop Time Response Using PID Controller Based on Z-N Tuning

The performance characteristics of closed loop nanopositioning system using different conventional controllers tuned by using frequency response method are given in table 1.

Type of controller	Rise Time (sec.)	Settling Time (sec.)	Maximum overshoot M_P (%)	Gain Margin (dB)	Phase margin (degree)	Bandwidth Hz
Proportional	0.0006	0.0659	96.1	3.94×10^{-5}	-0.0165	2.69×10^{3}
PI	0.0476	0.0908	0	-3.617	-14.90	42.89
PID	0.0227	0.0418	0	14.65	38.66	93.27
PID with first order filter	0.0227	0.0418	0	13.35	35.44	93.27
PID with derivative action in feedback path	0.0118	0.0226	0	∞	∞	192.7

Table 1 Performance Characteristics of Closed Loop Nanopositioning System Using Z-N Tuning

Analysis of table 1 depicts that only proportional action does not give any improvement in system performance, So, Integral controller is added to the Proportional controller to enhance the system performance. Problem of overshoot is almost removed by using PI controllers at the cost of instability of the system by having negative gain and phase margin. Introduction of derivative action results in PID controllers which significantly enhance the system performance. Further by having derivative action in feedback path, time response characteristics are further improved. Although time response characteristics using Z-N tuning algorithm are drastically improved over open loop performance but frequency response characteristics are not suitable because of infinity phase margin and demands for another type of tuning algorithm.

Fuzzy based PID controller:

Although arithmetic of PID controller, an industrial process controller, is simple and its stability is good, its dynamical characteristic is poor and it is not suitable for non linear applications. The fuzzy logic control method is a type of intelligent language control which does not rely on the mathematical model of the system and can deal with the nonlinearity of parameters and uncertain problems. It adopts manual control rules or rules established upon experts' experience and simulate logically consequent processes of human brain. The fuzzy logic control is flexible, robust and adaptive, however, its stability is insufficient. Because the stability of PID control is good and the dynamical characteristic of fuzzy logic control is good, a special controller known as Fuzzy based PID is formed by combing PID and Fuzzy logic controller [34].Schematics of fuzzy based PID is shown in figure 5.

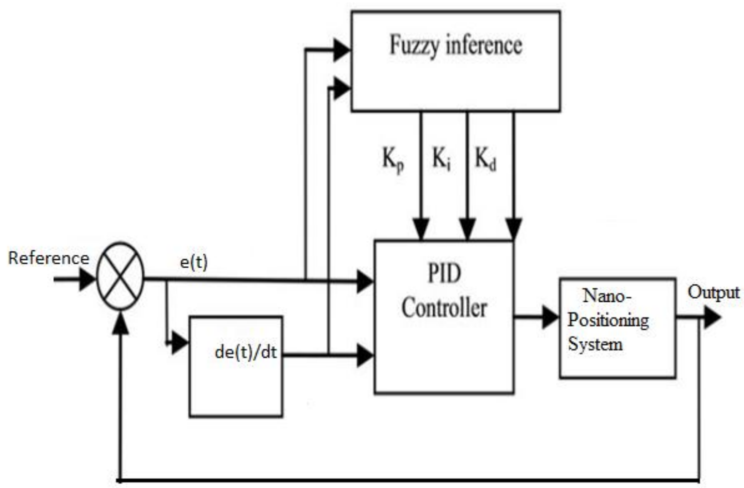

Figure 5. Configuration of Fuzzy PID Controller

When the error *e* is small, the fuzzy controller does not work. For large value of error, both fuzzy and PID controllers will work.In this paper, a fuzzy-PID controller is formed combining strong points of the two methods. This fuzzy-PID controller is applied to a one dimensional nanopositioning system to improve its time response characteristics.

IMPLEMENTATION OF FUZZY CONTROLLER

For the implementation of Fuzzy logic controller mathematical model of the system is not required but expert knowledge of the system behaviour is required to be known. Imprecision or vagueness in the input output description of the system can be described by the fuzzy sets. Fuzzy logic is much closer in spirit to human thinking and natural language than the traditional logical systems. Basically,it provides an effective means of capturing the approximate, inexact nature of the real world. Therefore, the essential part of the fuzzy logic controller is a set of linguistics control strategy based on expert knowledge into an automatic control strategy.Fuzzy controller design is composed of four important stages, namely,fuzzification interface, knowledge base, decision-making logic, and defuzzification interface [35-36]. The block diagram of fuzzy logic based nanopositioning system is shown in figure 6.

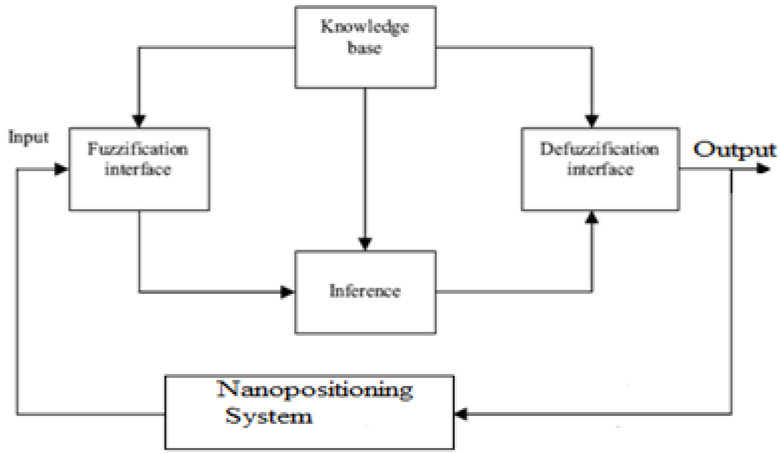

Figure 6 Block Diagram of Fuzzy Logic Based Nanopositioning System

The fuzzification interface converts crisp value inputs into fuzzy values or linguistic values. The knowledge base contains knowledge of the application domain and the control goals. It consists of a data base and a linguistic rule base.The data base contains necessary information which is used in control rules and data manipulation.The linguistic rule base defines the control strategy and goals by means of linguistic control rules. The decision making logic simulates the human decision-making procedure based on fuzzy concepts and Infers fuzzy control actions employing fuzzy implications and linguistic rules. Defuzzification yields a non-fuzzy control action from an inferred fuzzy control action and converts the range of output values into corresponding universe of discourse.

SIMULATION OF NANOPOSITIONING SYSTEM USING FUZZY LOGIC CONTROLLER

The simulink model and time response of nanopositioning system using fuzzy logic controller are shown in figures 7 and 8 respectively.

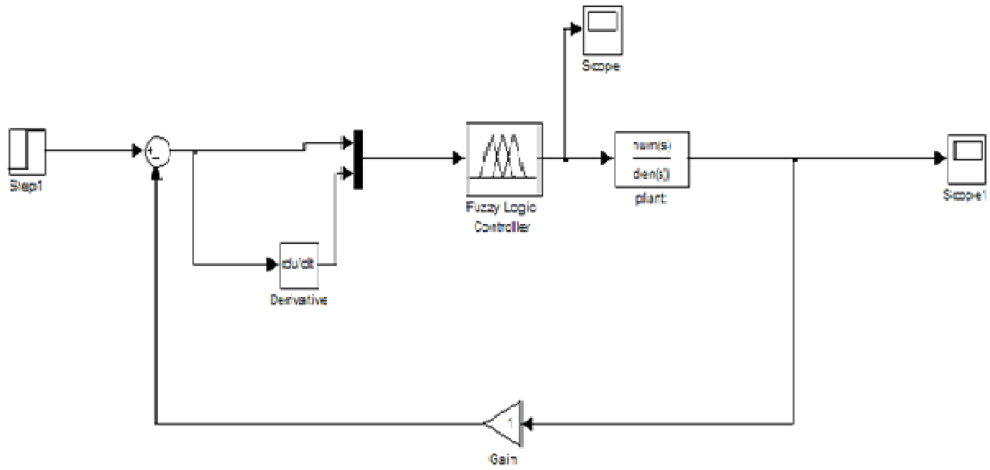

Figure 7Simulink Model of Nanopositioning System Using Fuzzy Logic Controller

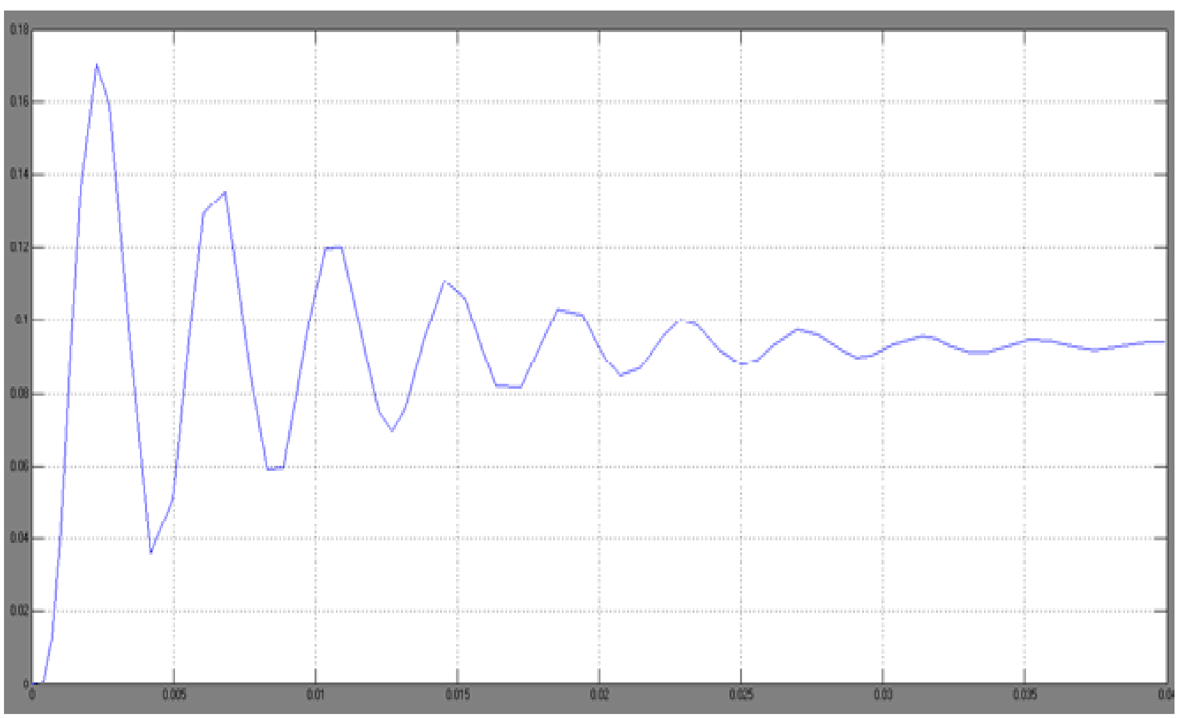

Figure 8 Time Response of Nanopositioning System Using Fuzzy Logic Controller

The time response of the system with fuzzy logic controller depicts very small improvement in the settling time of the nanopositioning system i.e 0.032 sec. as compared to 0.033 sec. for open loop nanopositioning system. The system characteristics can be further improved using Fuzzy based PID controller.

SIMULATION OF NANOPOSITIONING SYSTEM USING FUZZY LOGIC BASED PID CONTROLLER

The fuzzy control rule i.e the summary of the systemcontrol experience captures the expert's knowledgeabout how to control the system and it directly affects thequality of control system [5-8]. The fuzzy PID controller accepts two inputsi.e error e and derivative of error e ($\dot{e}$) and three outputs: proportional gain k_p, the integral gain k_i, thederivative gain k_d. The linguistic variables for inputs and outputs are named as Negative Big(NB), Negative Medium (NM), Negative Small (NS), Zero(ZO), Positive Small (PS), Positive Medium (PM), PositiveBig (PB). Fuzzycontrol rules are designed by considering tune principles such as: When error is greater than zero and $\dot{e}$ is less than zero, to obtain fast time response and to reduce steady state error faster $k_p$should be high andk_i, $k_d$should be smaller. When change in error is positive (error is increasing), the overshoot of thesystem is negative, $k_d$should be high, once the system is achieving itssteady-state,$k_d$should be decreased and k_p,$k_i$should be increased.

When the error is less than zero and change in error is also negative, the system is over steady-stateand tin order to decrease theovershoot, $k_d$should be bigger and ki, kpshould besmaller and when change in error is positive, the system is tending to reach atsteady-state, $k_p$should be high in orderto improvesystem's response speed and then access to steady-statequickly; $k_d$should be added to decrease theovershoot;$k_i$should be disconnected to minimize oscillationcaused by integral overshoot.

The simulation model of the fuzzy based PID control method for a nanopositioning systemis shown in figure 9.

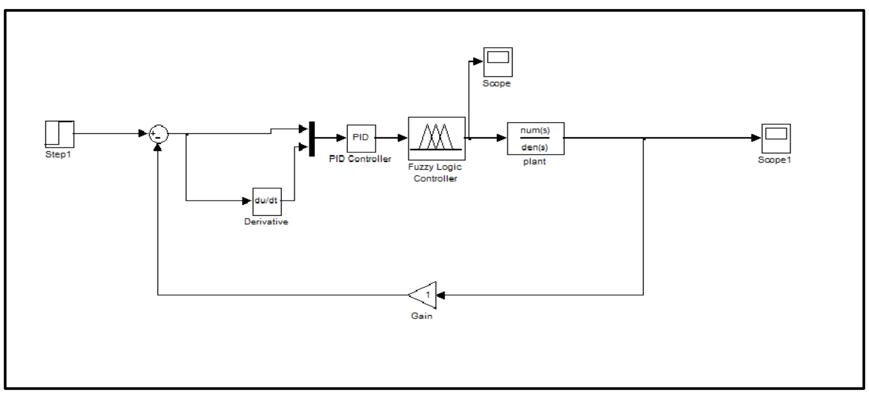

Figure 9 Simulink Model of Nanopositioning System Using Fuzzy Based PIDController

As per the fuzzy rules the time response of nanopositioning system using fuzzy based PI controller is shown in figure 10.

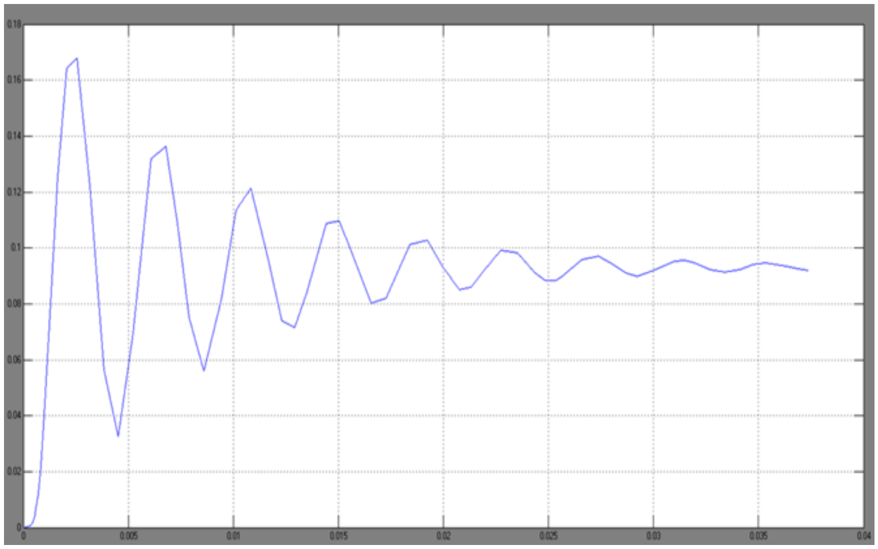

Figure 10 Time Response of Nanopositioning System Using Fuzzy and PI Controller

The time response of nanopositioning system by usingcomposite fuzzy and PI depicts that settling time and overshoot have been reduced, the effect of derivative action along with PI controller on nanopositioning system is shown in figure 11.

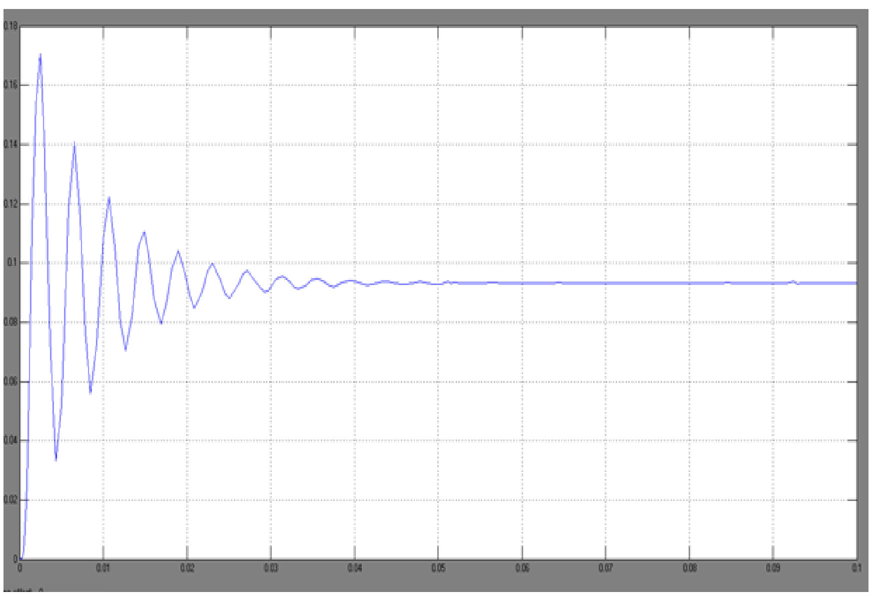

Figure 11 Time Response of Nanopositioning System Using Fuzzy BasedPID Controller

The time response of nanopositioning system with fuzzy based PID controller depicts the substantial improvement in settling time of nanopositioning system i.e approximately 0.0256 sec. as compared to 0.0335 sec for open loop nanopositioning system.

CONCLUSION

In this paper, a nanopositioning system consisting of piezoelectric actuator, sensor and motion guiding stage has been identified. Dynamic characteristics of open loop nanopositioning system have been analysed using time and frequency responses of the open loop system. It has been observed that open loop nanopositioning system has very high value of maximum overshot and settling time. Different control schemes such as conventional P, PI and PID controller have been simulated and implemented using MATLAB software to improve dynamic characteristics of nanopositioning system. But all these controllers are unable to give satisfactory results, so intelligent controller i.e fuzzy logic based PID controller is simulated and implemented on nanopositioning system to get satisfactory results. It has been observed that fuzzy based PID controller gives a substantial improvement in setting time as compared to conventional controllers.

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