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System Identification and Creep Compensation of Nanopositioning System Using Proportional and Double Integral Action

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Abstract: Nanotechnology is precision control and manipulation of devices and materials at nanoscale i.e. nanopositioning. Nanopositioners are precision mechatronics 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 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 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 analysed. To improve the system characteristics feedback controllers are implemented and simulated. In this paper, PI and PII controllers are designed and system performances are investigated for different values of feedback gain. Step response and frequency response under variety of conditions are obtained to verify the effectiveness of these feedback controllers. A positioning system utilizing piezoelectric actuators typically exhibits creep, hysteresis and lightly damped vibration modes which limits the usable bandwidth. In this paper, in order to control the creep nonlinearity, different controllers are implemented. Then a comparative study of traditional P and PI controller with PII controller on the basis of time and frequency response is given to show which controller is better. Simulation results for the performance analysis are carried out in MATLAB.

Keywords: Nanotechnology, nanopositioning, piezoelectric actuators, feedback controller, PI controller, PII controller, Nonlinearities, Creep.

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. Nanotechnology is the design, characterization, production and application of structures, devices and systems by controlling shapes and size at nanometer scale that produces structures, devices, and systems with at least one novel/superior characteristic or property [1]. Its applications are high-resolution motion control in adaptive optics, in modern hard disk drive systems, and in the production and inspection of high-density semiconductor designs. It include the alignment of optical fibre, optical beam pointing, positioning in scanning probe microscopes (SPMs) and nanofabrication.

The ability to image, control and measure at nanoscale is fundamental to nanotechnology Research and Development. 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. 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 nanometre [2,3]. A nanopositioning device consists of a sensor to measure the position of the nanopositioning stage (flexure guided mechanisms) and an actuator to convert the electrical signal produced by the controller in the physical signal needed by the positioning system having nano - scale resolution.

Nanopositioning devices ubiquitously use piezoelectric actuators as such actuators enable fast and frictionless motion. Piezoelectric actuators are as such ideal for high resolution positioning tasks. As piezoelectric actuators can produce large forces, provide frictionless motion, the resolution is only limited by instrumentation noise, they are ideal for high bandwidth, high-resolution positioning [2,3]. Highly efficient and inexpensive sensors at nanometre scale such as Piezoresistive, optical, capacitive, thermal and inductive are widely used [3,4]. Here, piezoelectric sensor is used due its high sensitivity and resolution to measure displacement.

II. MODELING OF NANOPOSITIONING SYSTEM

A typical nanopositioning system consists of a flexure guided mechanism, sensor actuator and control system to control the performance of system. The mechanical

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diagram of a single axis positioner is shown in Figure 1. The model is derived for the single degree-of-freedom lateral positioning platform as illustrated in figure 1. 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 [3-5]. 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.

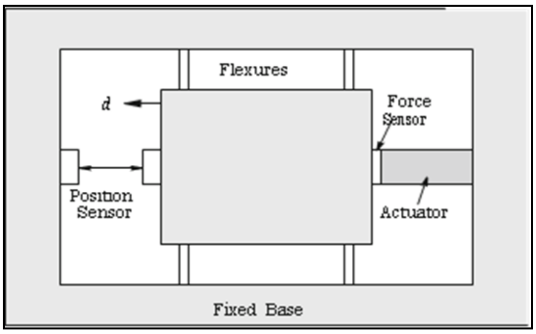

Figure1

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 [6,7]. The dynamics of the suspended platform governed by Newton's second law is given as

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

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

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

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

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

The equation of motion is then

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

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

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

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

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

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,

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

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

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

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

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

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.

III. DYNAMICS OF OPEN LOOP SYSTEM

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

$$G_{dva} = \frac{7.5}{0.102S^2+200s+1.75\times10^8} \qquad (11)$$

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

$$G_{v_s v_a} = \frac{V_s}{V_a} = \frac{(0.142S^2+142.5S+71.25\times10^6)}{0.1025S^2+200S+175\times10^8} \qquad (12)$$

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 2 and 3 respectively.

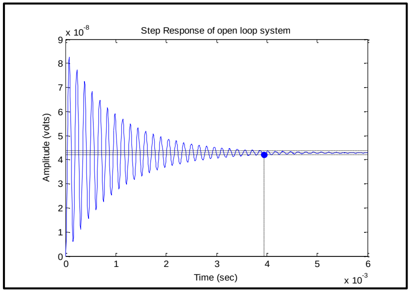

Figure 2 Step Response of The Open Loop System

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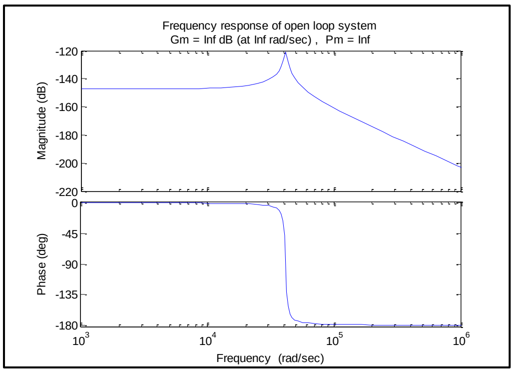

Figure 3 Frequency Response of the open loop system

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.

IV. CONTROL OF NANOPOSITIONING SYSTEM

A variety of control approaches can be used to improve the positioning performance of nanopositioning devices. In closed loop system a part of actual output of the system is feedback to the input where it is compared with reference input signal. The feedback control system can use proportional controller, proportional integral (PI) or proportional Integral - Integral (PII) controller to make output signal y tracks the reference signal r [3,8]. These controllers provide high gain at low frequencies and greatly reduce the effect of hysteresis and creep non-linearity. P controller reduces the value of time constant and makes the system response faster, but it produces offset or steady state error.

The combination of proportional and integral terms increases the speed of the response and eliminates the steady state error. Feedback system using integral or proportional integral controller is the most popular technique for the control of commercial nanopositioning devices. Closed loop stability can be improved by using PI controller which has transfer function (k_p+k_i/s) where k_p and k_i are the proportional and integral controller gain respectively.

PI controller will eliminate forced oscillations and steady state error resulting in operation of on-off controller and P controller respectively. PI controller improves the system characteristics by giving no maximum overshoot but has little high value of settling time [9-10].

PII is the combination of proportional control action and two integral control actions. This is type of controller is basically employed in controlling the non linearities of the system. Since PID controllers have problems controlling nonlinear processes. We can see that when output is low the PID controller reacts slowly. In the middle range the PID settings are correct. In the top of the characteristic the process is much faster resulting in overshoot of the process. So, instead of derivative action, the performance improvement of the nano-system can be further achieved by using double integral action along with proportional action i. e PII controller [11-14].

Generally the traditional control design approach consists of varying the controller's transfer function until a desired closed loop performance is achieved. For PII controller with transfer function [(K_p*t_i*s^2 + K_i*s + K_i) / s^2], performance characteristics of the system is obtained from time and frequency response for different values of controller gain and time constant. It can be observed that rise time, settling time and maximum overshoot of the system considerably decreases with the increase in feedback gain.

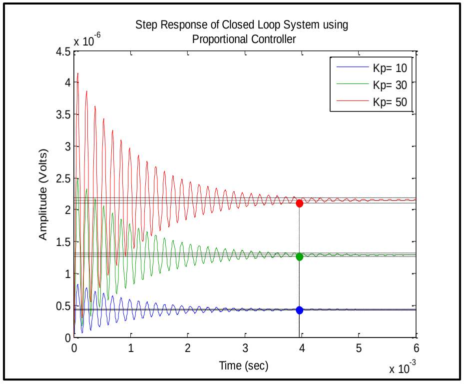

Figure 4 Step Response of the closed loop system with P Controller

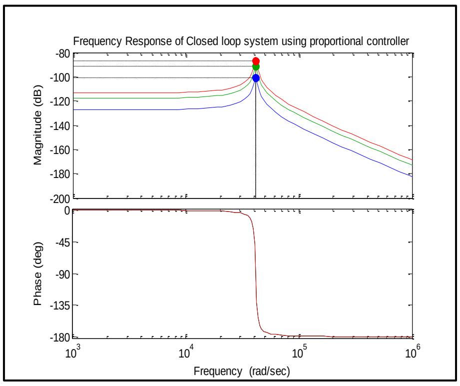

Figure 5 Frequency Response of the closed loop system with P Controller

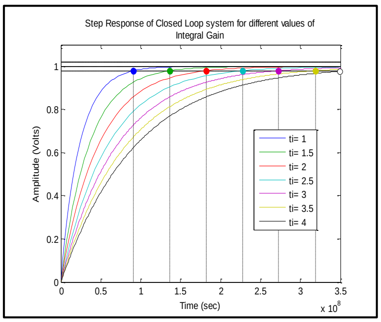

Figure 6 Step Response of the closed loop system with PI-Controller

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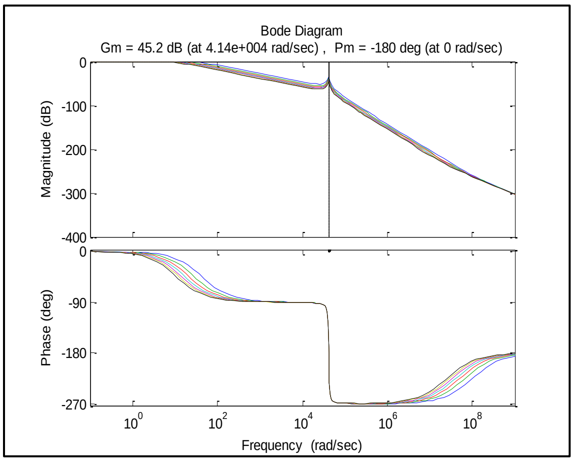

Figure 7 Frequency Response of the closed loop system with PI Controller

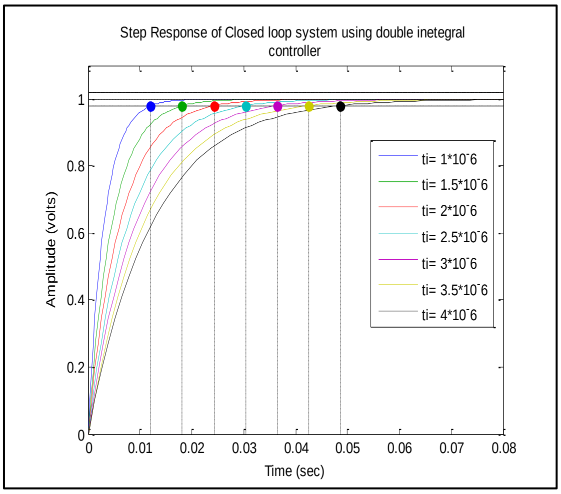

Figure 8 Step Response of the closed loop system with PII-Controller

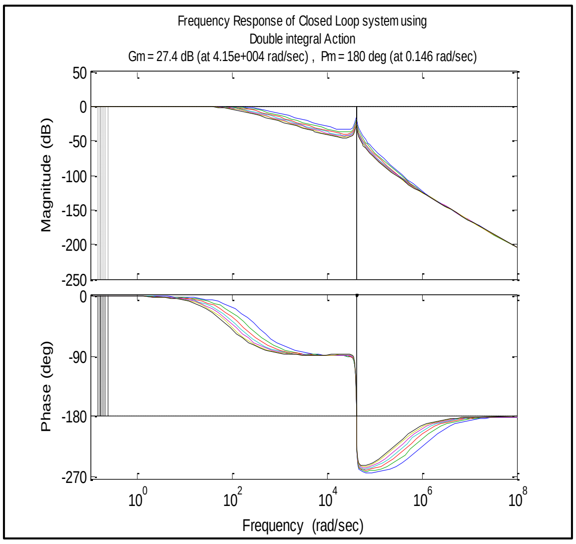

Figure 9 Frequency Response of the closed loop system with PII Controller

The comparison between different types of controllers on the basis of the time and frequency response is shown in the table 2.

TABLE 2: PERFORMANCE CHARACTERISTICS COMPARISON NANOPOSITIONING SYSTEM USING DIFFERENT CONTROLLERS

System Response	Settling Time (second)	Maximum Overshoot	Gain Margin (db)	Phase Margin (degree)
Open Loop	0.0060	92.8204	Infinity	Infinity
P-Controller	0.0060	92.8204	Infinity	Infinity
PI-Controller	0.8198	0	58	-180
PII-Controller	0.0482	0	27.1	180

By comparing the results of closed loop system using different types of controllers as shown in table 2, it can be concluded that proportional controller gives no improvement in the system performance over open loop system. Use of integral action with proportional action improves the system performance significantly by improving gain and phase margin and completely eliminates maximum overshoot but increases the settling time. Moreover, it requires higher values of tuning parameter K_ii.e controller gain to improve system characteristics. Drastic improvement in system characteristics has been observed by using PII controller. The decrease in the settling time causing the speeding up of the system has been obtained with smaller values of gain K_i of PII controller. Increase in the gain and phase margins are significant and improve the stability of the system.

V. MODELING AND CONTROL OF CREEP NON LINEARITY

The input-to-output behaviour of a piezoelectric actuator consists of three non-linear effects: creep, hysteresis, and vibrational dynamics [16,17]. When an input voltage is applied to a piezo electric actuator, the actuator's output displacement exhibits the combined effects of hysteresis, creep, and vibration. These three effects are coupled and the degree by which they appear in the output response depends on the input frequency and output range. This is an importance concept when designing with piezo-electric based devices. Hysteresis is significant when the range of motion of a piezo-actuator is large. At high operating speeds, the effect of the vibrational dynamics becomes noticeable. On the other hand, when a piezoelectric actuator operates over long periods of time, then creep is significant.

When a large offset voltage is applied to a piezoelectric actuator, it first responds very quickly, by moving to the intended position, which corresponds to the applied voltage. However, the actuator then slowly creeps (over an extended period of time) to a new value [18]. This phenomenon can adversely affect the resulting image, particularly during slow scans. The creep effect decreases with time. During open-loop scans, two practical ways to avoid creep are to avoid application of a large offset voltage to the actuator and to scan an image at relatively high rates, e.g., above1 Hz. However, different types of controllers can be used to decrease the effect of creep and hence to improve the system performance {19-21].

A. Modeling of Creep

Creep and vibrational dynamics effects of piezo-electric actuator can be modeled by using mass, spring, and damper elements as shown in figure 9

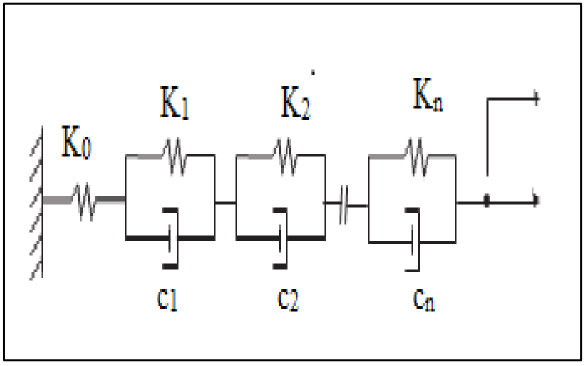

Figure 9 Modelingofcreep non linearity of piezoelectric actuator

The transfer function model for creep in terms of the spring and damper elements is {17]

$$G_{creep} = \frac{1}{K_o} + \sum_{i=1}^{n} \frac{1}{SC_i + K_i} \qquad (13)$$

Where ki and ci are the spring and damper constants, respectively shown in the figure 9. The open loop transfer function of the system with creep is given as

$$G_{openloop} = G_{creep} * G_p \qquad (14)$$

$G_p$dynamic process transfer function and G_{creep} is creep model transfer function.

By assuming the practical values of system parameters as ko =50N/um k_1=100 N/um C_1=100 N/ms-1, the first order transfer function of creep model is given as:

$$G_{creep} = \frac{0.02S+0.03}{S+1} \qquad (15)$$

The transfer function of output actuator displacement and input applied voltage of piezoelectric actuator with creep non linearity is given as:

$$G_{openloop} = G_{creep} * G_{dva} \qquad (16)$$

The open loop time response of piezo-electric actuator with creep non linearity is given by figure 10.

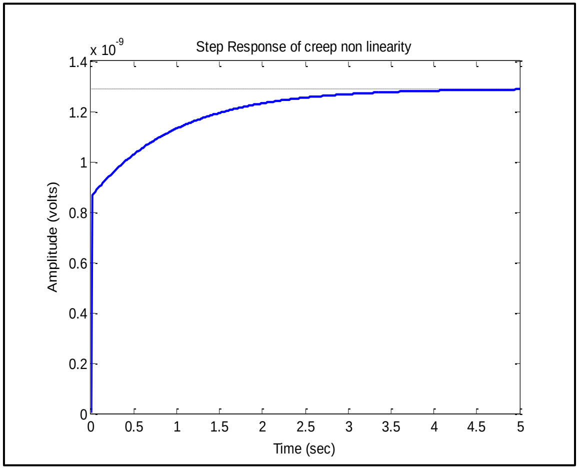

Figure 10 Step Response of the open loop nanopositioning system with creep

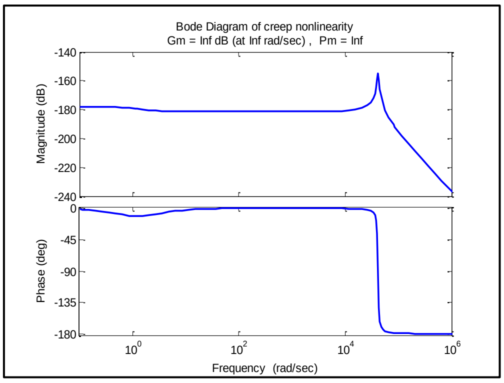

Figure 11Frequency Response of the open loop system with creep

The nonlinearities of nanopositioning system are controlled by using PI and PII controllers. The time and frequency response of the closed loop nanopositioning system along with creep nonlinearity using Pi and PII controllers are shown in figures 12, 13, 14 and 15.

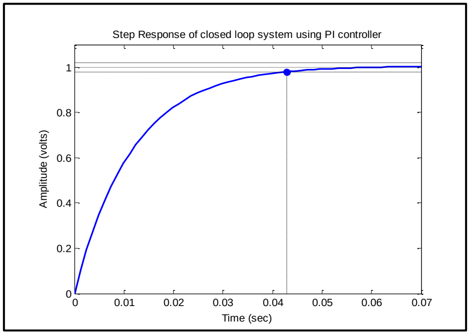

Figure 12Step Response of the closed loop creep system with PI-Controller

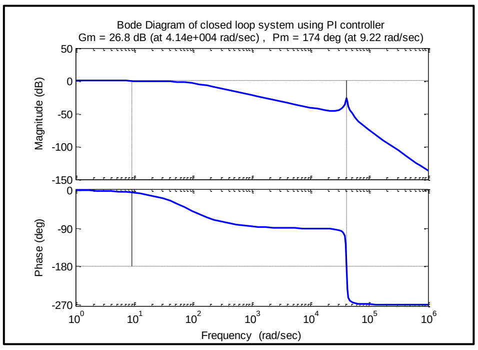

Figure 13Frequency Response of the closed loop system with creep PI-controller

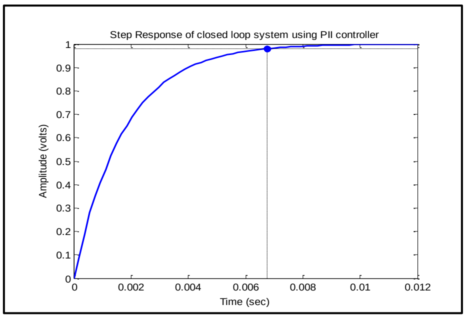

Figure 14Step Response of the closed loop creep system with PII- Controller

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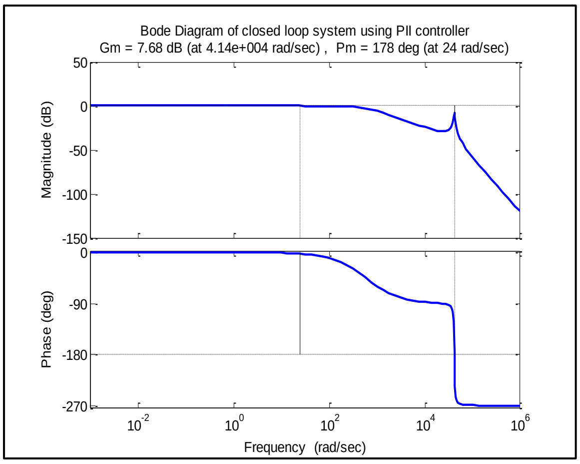

Figure 15 Frequency Response of the closed loop creep system with PII-controller

The comparison between different types of controllers on the basis of the time and frequency response obtained is shown in the given table 3.

TABLE 3: COMPARISON BETWEEN RESPONSES OF DIFFERENT CONTROLLERS

System Response	Settling Time (sec.)	Maximum Overshoot	Gain Margin (db)	Phase Marin (degree)
Open Loop	2.8134	0	Infinity	Infinity
P Controller	2.8134	0	Infinity	Infinity
PI-Controller	0.0429	0.5051	26.4	174
PII-Controller	0.0068	0	7.68	178

VI. CONCLUSION AND RESULTS

Analysis of closed loop response of nanopositioning system with creep as shown in table 3, it has been observed that proportional controller gives hardly any improvement in the system characteristics and in control of creep nonlinearity occurring in the system. Use of integral controller with proportional action improves the system performance significantly by improving gain and phase margin but slightly increases in maximum overshoot of the system. Moreover, it also requires higher values of tuning parameter Ki i.e controller gain to obtain the desired response. Drastic change in characteristics has been observed by using PII controller. The decrease in the settling time causing fast response of the systemhas been obtained with smaller values of gain Ki of the double integral control. Therefore, creep effect decreases with time. Improvement in gain and phase margins are significant and hence improvement in the system stability.

REFERENCES

[1]. Sheilza Jain, AkhileshSwarup, ManeeshaGarg, 2013, “Design and Simulation of Robust Controller for Flexure Stage Based Piezo-Actuated Nanopositioning Device”, International Journal of Control and Automation, Vol. 6 (2), pp. 17-28

[2]. M. Yves, 1995, “Scanning Probe Microscopes”, Bellingham, WA: SPIE. M. Sitti, 2001, “Survey of nanomanipulation systems”, Proceeding IEEE Conference on Nanotechnology,pp. 75−80.

[3]. S. Devasia, E. Eleftheriou, S. O. Reza Moheimani, 2007, “A Surveyof control issues in nanopositioning”, IEEE transaction onControl System Technology, Vol. 15 (5), pp. 802-823.

[4]. Baxter LK, 1997, “capacitive sensors: Design and applications”, IEEE Press, Piscataway.

[5]. S.O.R. Moheimani, A.J. Fleming, 2009,“Piezoelectric transducers for vibration control and damping”.Springer, Berlin.

[6]. A.J. Fleming, 2008,“Techniques and considerations for driving piezoelectric actuators at high-speed”.

[7]. A. J. Fleming, 2010, “Nanopositioning system with force feedback for high-performance tracking and vibration control,” IEEE/ASME Transaction on Mechatronics,vol. 15, no. 3, pp. 421–432.

[8]. A. J. Fleming and A. G. Wills, 2009, “Optimal periodic trajectories for band limited systems,” IEEE Transaction on Control System and Technology, vol. 13, no. 3,pp. 552–562.

[9]. Sheilza Jain, AkhileshSwarup, ManeeshaGarg,2013, “Design of feedback controller for non-minimum phase nano positioning system”, Advanced Material Letters, Vol. 4(1), pp. 31-34.

[10]. AshishTiwari, 2002, In Modern Control Design, John Wiley & sons Pte. Ltd. Singapore, pp. 437-466.

[11]. ShobhitV.,Wonjong Kim, Jie-Gu,2004, IEEE/ASME transaction on mechatronics, Vol.9, no (2), pp 384-89.

[12]. B. Shapiro, 2005, “Workshop on control of micro- and nano-scale systems”, IEEE Control System Magazine, Vol. 25, no. 2, pp. 82–88.

[13]. H. J. M. T. A. Adriaens, W. L. de Koning, and R. Banning, 2000, “ModelingPiezoelectric Actuators”, IEEE/ASME Transactions onMechatronics, Vol.5,no. 4, pp. 331–341.

[14]. S. S. Aphale, B. Bhikkaji, and S. O. R. Moheimani. 2008, “Minimizing Scanning Errors in Piezoelectric Stack-Actuated Nanopositioning Platforms” ,IEEE Transactions on Nanotechnology, Vol. 7(1), pp.79–90.

[15]. C.H. Liu, W.Y. Jywe, Y.R. Jeng, T.H. Hsu and Y. T. liu, 2010, “Design and control of a long travelling nanopositioning stage,” Precision Engineering, Vol. 34, pp. 497-506, 2010.

[16]. S. S. Aphale, S. Devasia, and S. O. R. Moheimani, 2008, “High-Bandwidth Control of a Piezoelectric Nanopositioning Stage in the Presence of plant uncertainties”, IEEE transaction on Nanotechnology.

[17]. H. Jung and D.G. Gweon, “Creep characteristics of piezoelectric actuators,” Review of Scientific Instruments, vol. 71, pp. 1896–1900, April 2000.

[18]. O. M. E. Rifai and K. Youcef-Toumi, “Creep in piezoelectric scanners of atomic force microscopes,” Proceeding of American Control Conference, (Anchorage, AK), pp. 3777– 3782, May 8-10, 2002

[19]. D. Croft, G. Shed, and S. Devasia, “Creep, hysteresis, and vibration compensation for piezoactuators: Atomic force microscopy application,” ASME Journal of Dynamic System Control, Vol. 123(1), pp. 35–43, 2001.

[20]. K.K. Leang, S. Devasia, “Feedback- Linearized inverse feedforward for creep, hysteresis and vibration compensation in AFM piezoactuators,” IEEE Transaction on Control System Technology, Vol.15 (5), pp. 927-935, 2007

[21]. K. Leang and S. Devasia, “Hysteresis, creep, and vibration compensation for piezoactuators: Feedback and feedforward control,” in Proceeding of 2nd IFAC Conference Mechatronics System, pp. 283–289, 2002