Research Article Adv. Mat. Lett. 2013, **4**(1), 31-34 ADVANCED MATERIALS ***Letters***

www.amlett.org, www.amlett.com, DOI: 10.5185/amlett.2013.icnano.217

Design of feedback controller for non-minimum phase nano positioning system

Sheilza Aggarwal[1], Maneesha Garg[2], Akhilesh Swarup[3]

[1]Electronics Department, [2]Humanities and Applied Science Department, YMCA University of Science and Technology, Faridabad 121006, India
[3]Electrical Department, National Institute of Technology, Kurukshetra 132119, India

*Corresponding Author Tel: (+91) 9818886957; E mail address: sheilzajain@indiatimes.com

ABSTRACT

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 Linear Variable Differential Transformer (LVDT) as a 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. Step response and frequency response under variety of conditions are obtained to verify the effectiveness of the proposed controllers. In this paper PI and PI2 controllers are designed and system performances are investigated for different values of feedback gain. Unfortunately nanopositioners operating in closed loop achieve high bandwidth at the cost of increased sensitivity to the measurement noise and hence reduced resolution. In this paper H infinity controller is analyzed and performance of the device is studied. Then a comparative study of traditional PI and PI2 controller with H infinity 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. Copyright © 2013 VBRI press.

Keywords: Nanopositioning; piezo-actuators; closed loop system; PI controller; PII controller; H- infinity controller.

Sheilza Aggarwal did B.Tech in Electronics and Communication Engineering from Kurukshetra University, India and M.Tech with specialization in Control System from Maharishi Dayanand University, India. Presently she is working as Assistant Professor in Electronics Engineering Department at YMCA UST Faridabad and is pursuing Ph.D in Nano-positioning from Maharishi Dayanand University.

Maneesha Garg did her Ph.D. (Physics) in 2002 from Kurukshetra University, India. After that she worked as Research Associate granted by CSIR, in NIT Kurukshetra for 4 years. She has 18 publications in national, international journals and more than 30 papers in conferences to her credit. Presently she is working as Assistant Professor in Humanities and Applied Science Department, YMCA UST, Faridabad and guiding 4 scholars for their research work.

A. Swarup received B.E. in Electrical Engineering from MN Regional Engg. College, Allahabad and M. Tech. with specialization in Control Systems from IT-BHU, Varanasi, India. He obtained his Ph.D. from IIT Delhi in the area of Robotic Control. He is serving at National Institute of Technology Kurukshetra since 1981. Presently he is working as Professor of Electrical Engineering and Dean (Research & Consultancy). His areas of research interest are Robotic Control, Robust Control and Navigational Control. He is Senior Member of IEEE and Member of its Control System Society. Also, he is Life Member of Systems Society of India (SSI) and Indian Society for Technical Education (ISTE).

Introduction

In the modern era of nanosystems, precise manufacturing of nanoparts is a very critical task. Manipulation of objects at nanoscale is the most important factor that limits the precise manufacturing of nanoparts **[1].** In all applications of nanotechnology precise control and manipulation of devices and materials at nanoscale i.e. nanopositioning plays an imperative role. Fine resolution and high accuracy are essential features in positioning applications **[2].** Nanopositioner has numerous applications in Scanning probe Microscopy (SPM), laser beam alignment, micromaniputation, defense, biotechnology, information technology, chemical industries, photonics and test application in the semiconductor devices **[3, 4].** Nanopositioners are also used to manipulate atomic and molecular scale structure including bio- molecules and to characterize surface properties of materials **[5].** Fast response of nanopositioner is important in applications such as manipulator's pick and place operation near a wall, filling a tank with fluid in minimum time without spilling over etc. For distortion free imaging and accurate metrology these applications need to the development of closed loop control based on position sensing techniques for subnanometer and nanometer resolution. Ultra precise nanopositioning systems, sensors, actuators and motion controllers are prime elements for instrumentation such as scanning probe microscope, optical microscope, profilometers, dual storage servo system of HDDs and critical dimension measuring tools etc **[6].**

Theory and modeling

Device description

To investigate matters at nanometer or subnanometer scale, the key component is the nanopositioning stage that can be used to scan or position the sample precisely. Typically nanopositioning stage makes the use of piezoelectric actuators because of their high stiffness, compact size and effectively infinite resolution **[7]**. In general a nanopositioning device used in scanning probe microscopy (SPM) comprised of flexure stage, an evaluation stage, a piezo actuator, LVDT as sensor and control system **[5, 8].** Flexure stage with sample holder must be designed in such a way so that flexures and hence sample can move in the linear and angular axes. The displacement of the flexure stage is sensed by the LVDT which converts this displacement into electrical signal for further processing. The evaluation stage consists of an Atomic Force Microscope (AFM) head which is placed above the sample holder. Movement of sample under the tip of AFM causes the cantilever to deflect in vertical direction. The resulting deflection is converted into the voltage which can be used to determine the topography of the surface. Control system must be designed to guarantee a high precision positioning under variable operating condition and hence makes the tracking error small so that the difference between desired and actual displacement is small. Depending upon control strategy, the system will give different values of performance characteristics.

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 LVDT 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. The input to the amplifier is restricted to 0 ⩽ V ⩽ -10V in magnitude because piezo stacks saturates beyond this limit and leads to a travel range of approximately 75µm **[5].** Piezo-electric materials such as quartz and lead Zirconium Titanate (PZT) produce electric potential when they are subjected to mechanical vibration. Same material produces mechanical changes in its crystal lattice if electric field is applied to it. These mechanical deformations of piezoelectric actuator are used for positioning with high accuracy.

Piezo actuators have number of advantages such as do not suffer from wear and tear, require very little power and maintenance, have fast response time, are operable in a wide range of temperature, are not affected by magnetic fields and provides repeatable subnanometer resolution in displacement at high frequency **[7-9].** Since PZT do not have any sliding parts, therefore are immune from undesirable back-lash effect and stick- slip motion. But applications of piezoelectric actuators for precision positioning in nanopositioning systems are reduced because of presence of inherent non- ideal characteristics such as hysteresis between displacement and electric field, drift due to creep, temperature effect and mechanical resonance. The aforementioned limitations hindered the use of piezo-electric actuators for long scanning range and high speed operations. As a result of these problems practical nanopositioning systems require feedback / closed loop controls to obtain satisfactory performance. Various feedback control techniques can be used to improve precision and speed of such systems.

Modeling of nanopositioning device

Modeling of the device is done when the device operates in the linear region of its characteristics. Device is modeled using its frequency response. Offset of the device to operate about the null position is -5V. The presented model adequately represents the dynamics of the system which can be approximated by fourth order transfer function given as [**5**]

$$G(S)=\frac{9.7\times10^{4}\left(s-(7.2\pm7.4i)\times10^{3}\right)}{(s+(1.9\pm4.5i)\times10^{3})(s+(0.12\pm15.2i)\times10^{2})} \qquad (1)$$

This is a non- minimum phase (NMP) transfer function having one zero in the right half s-plane (RHP) which pose limitations on the performance specifications of the device. The time and frequency response performance characteristics of the open loop system are described in **[8].**

Time response analysis of open loop system gives settling time 0.0335 seconds and overshoots of 83.6016 which is very large and must be avoided using control techniques. Analysis of frequency response gives phase margin of 27.2 degree and gain margin of 4.63dB at gain crossover frequency of 1.61×103 rad/sec and at phase crossover frequency of 1.74×103 rad/sec respectively. Very small variation in the frequency response of the system from DC signal to AC signal is also observed.

Control design

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 error signal is applied to the controller. Controller controls the manipulated variable so that there is zero deviation between controlled output and desired output. Block diagram of the closed loop system is given in **Fig. 1**. Here Piezo- actuator, nano positioning device and LVDT sensor represents the nanopositioning system, r is the tracking - reference signal, d is the mechanical disturbances, n represents the sensor noise, ym is the noisy measurement signal and K is the transfer function of controller. 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 **[9].** Fast speed, increases in bandwidth, subnanometer resolution and reduction of effects of nonlinearity are the prime objectives of feedback system. It can be seen that speed of the system is governed by the dominant poles.

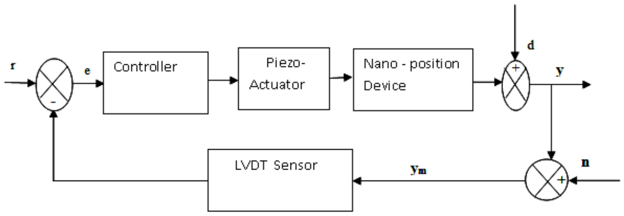

Fig. 1. Block diagram of closed loop control system.

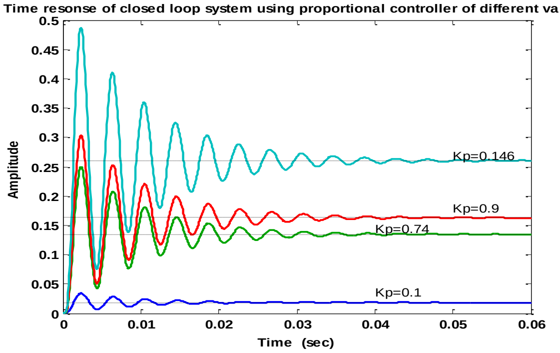

Fig. 2. Time Response of Nanopositioning System with PI Controller for different values of feedback gain H

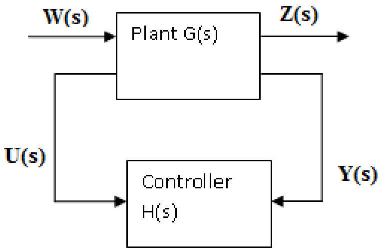

Fig. 3. Block diagram of generalized plant for H- infinity controller.

Proportional controller

Presence of RHP zero imposes a fundamental limitation on the performance of this system. Because of RHP zero maximum value of feedback gain used for such system is about 0.1670. Time response curves for closed loop system using proportional controller of different values are shown in **Fig. 2**. By analyzing this curve it can be seen that decrease in value of proportional controller gain Kp from 1.46 to 0.1 gives decrease in settling time and maximum overshoot. Frequency response curve for the same system is given in **Fig. 3**.

From the analysis of **Fig. 3** it can be concluded that the decrease in value of Kp increase the gain margin and phase margin. Time and frequency response characteristics of the system are given by **Table 1**. Bandwidth of the system decreases with the increase in value of Kp. Further increase in value of Kp i.e. more than 1.46, the closed loop system gives negative phase margin and hence system becomes unstable. The performance characteristics of closed loop system using proportional controller does not give significant improvement over open loop system.

Table 1. Comparison of performance parameters of closed loop system using PI controller for different value of H.

Controller gain Kp	**Settling Time (Sec)**	**Maximum overshoot**	**Bandwidth (Hz)**	**Gain Margin**	**Phase Margin**
1.46	0.389	87.20	2.54×10^{3}	1.00	0.254
0.9	0.0358	85.76	2.53×10^{3}	1.72	28.61
0.74	0.0354	85.34	2.51×10^{3}	2.13	63.56
0.73	0.0353	85.32	2.51×10^{3}	2.16	∞
0.1	0.0335	83.34	2.49×10^{3}	16.88	∞

Proportional integral controller

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 (kp+ki/s) where kp and ki are the proportional and integral controller gain respectively. For kp = 0.01, ki=75, the maximum value of feedback gain H is 0.1674 and after this value of feedback gain, system becomes unstable. Characteristics of the system obtained by time and frequency response of the closed loop system using PI controller for different values of feedback gain H are depicted in **Table 1**.

Analysis of **Table 1** shows that as feedback gain H increases, phase margin increases, gain margin moderately decreases. Increase in bandwidth by increasing the feedback gain is also observed. It can be seen that PI controller eliminates overshoot completely and settling time is much better as compared to proportional controller.

Proportional integral-integral (PII) controller

The performance improvement of the nano-system can be further achieved by using PII controller. 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 [(0.01S2 + 450S + 100) / S2], performance characteristics of the system obtained from time and frequency response for different values of feedback gain H are given in **Table 2**. It can be observed that rise time, settling time and maximum overshoot of the system considerably decreases with the increase in feedback gain. All these characteristics improve the speed of the system. Further as seen from **Table 2** values of gain margin shows marginally decrease in the value and phase margins shows the moderate increase in its value resulting in a stable system. Bandwidth of the system shows satisfactory improvement over PI controller.

Table 2. Comparison of performance parameters of closed loop system using PII controller for different values of H.

Feed-back gain H	Gain margin(dB)	phase margin (degree)	Rise time (sec.)	Settling time (sec.)	Band-width (Hz)	Maximum overshoot
0.1220	2.387	96.012	0.197	0.321	10.451	1.9028
0.1420	2.367	97.169	0.172	0.285	12.131	1.6567
0.1670	2.342	98.621	0.148	0.249	14.234	1.4293
0.1870	2.322	99.788	0.133	0.226	15.917	1.287

H- infinity controller

The H∞ optimal control design technique directly handles the problems of robustness by driving controller which maintains system response and error signal within prescribed tolerances despite the presence of noise in the system **[10].** The sensitivity of the output with respect to the noise depends on the sensitivity matrix of the output. The robustness of the closed loop system with respect to the process noise can be assured by minimizing the scalar norms of the sensitivity matrix. To design H∞ controller, consider the generalized form of plant as shown in **Fig. 2**. In this figure, plant is represented by transfer function G(s), input and output vector are U(s) and Y(s) respectively, H(s) is the transfer function of controller. Vector W(s) contains all inputs external to the closed loop system and desired output vector. Vector Z(s) consists of all errors e(s) that determine the behavior of the closed loop system. To obtain performance objectives and physical constraints, the regulated outputs are scaled with the weighted transfer function. Sensitivity function S is scaled by W1, complementary sensitivity function T is scales by transfer function W2 and transfer function KS is scaled by transfer function W3. W1 and W2 are chosen first order transfer function such that

$$W1(s) = \frac{0.1667s+2827}{s+2.827}, \quad W2(s) = \frac{s+235.6}{0.01s+1414}$$

and W3(s) is scaled by a constant weighting of 0.1 to restrict the magnitude of the input signal [**5**]. The transfer function of the controller can be obtained such that

$$\left\| \begin{matrix} W_1 S \\ W_2 T \\ W_3 KS \end{matrix} \right\|_\infty < \gamma$$

where S is the sensitivity function and T is the complementary sensitivity function. The controller is designed using MATLAB for $\gamma = 2.415$ and sixth order transfer function is obtained.

Performance specifications of time and frequency responses are tabulated in **Table 3** from which it is observed that increase in feedback gain is decreasing settling time and hence improves the speed of system. Increase in feedback gain H also increasing the phase margin for stability and it has little effect on the gain margin. Further improvement in bandwidth is also observed by increasing the feedback gain.

Table 3. Performance Characteristics of closed loop system using H-infinity controller for different values of H.

Feedback gain	Gain margin (dB)	phase margin (degree)	settling time (sec.)	Bandwidth (Hz)	Maximum overshoot
0.1274	9.22	84.40	0.1221	32.22	0
0.1674	9.18	86.61	0.0943	41.833	0
0.6	8.75	114.57	0.0252	159.88	0
1	8.35	∞	0.0131	298.30	0.0284

Conclusion

By comparing different types of controllers, it can be concluded that proportional controller gives hardly any improvement in the system performance over open loop system.. Use of integral controller with proportional action improves the system performance significantly by improving gain and phase margin and reducing maximum overshoot. Drastic change in characteristics has been observed by using H infinity controller. The decrease in the settling time causing the speeding up of the system has been obtained. Increase in the gain and phase margins are significant and improve the stability of the system.

Acknowledgments

We thank to the Department of Biotechnology, Jaypee Institute of Information Technology, Noida (India) and Dr. A.K. Panda from National Institute of Immunology, New Delhi (India) to support the research work.

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