Sudan University of Science & Technology
College of Graduate Studies

Closed Loop Control of Micro-electro Mechanical System (simulation study)

التحكم بدائرة مغلقة في نظام كهروميكانيكي مصغر(دراسة محاكاة)

Thesis Submitted in Partial Fulfillment for the Requirements of Master Degree (M.Sc.) in Electrical Engineering

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بِسْمِ اللّهِ الرَّحْمَنِ الرَّحِيمِ

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قال تعالى:

(وَقُل رَّبِّ زِدْنِي عِلْمًا)

صدق الله العظيم

سورة طه الآية (114)

Dedication

Dedication to my mother…

Whit warmth and faith...

Dedication to my father…

Whit love and respect …

Dedication to my friends..

Whom we cherish their friendship

Dedication to my special people

Who mean so much to me…

Dedication to all my teachers …

In whom I believe so much …

Acknowledgement

First of all, we would like to grate our supervisor

Dr. Mousab Zaroog

Who always offered support and ideas to make the project succeeds.

In Addition we must grate

OurStaff for his helpful in this project and all engineers whom introduced their assistances for us.

Special thanks for Sudan University for its great staff and laboratories that play a backbone in our research.

Abstract

Micro-electro-mechanical system (MEMS) actuators are used in a wide variety of commercial, military and industrial products. Electrostatic, thermal, electromagnetic and piezoelectric mechanisms, due to scalability and fabrication simplicity, are used extensively for actuation in many applications that contains feedback controllers. The aim of this research is designing and simulating a closed loop control system for micro-electromechanical beam based on Matlab Simulink, in order to investigate the stability of the MEMS system with a variation of voltage to prove the stability of closed loop control for repetitive control of an electrostatic micro bridge actuator and the non-linear control of MEMS. The evaluation of performance done for one system based on their structures.

المستخلص

انظمة الكهروميكانيكية المصغرة(MEMS) تعتبر من الانظمة المنتشر استخدامها في العديد من المجالات منها التجارية، والصناعية ، والعسكري نظرا للحجم الصغير جدا وسهولة التصميم والاستقرار.الهدف من هذه الدراسةإثبات الاستقرار للانظمة الكهروميكانيكية المصغرة(MEMS) باستخدام برنامج للمحاكاة Matlab –Simulink وقد تم اختيار نظامي (Repetitive Control of an electrostatic micro bridge actuator and the non-linear Control of MEMS)). وتصميم الهيكل العام لنظام واحد باستخدام برنامج المحاكاة.

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Abbreviations

MEMS	Micro-electro-mechanical systems
NEMS	Nano-electro-mechanical systems
MIMO	Multiple input multiple output
2-D	two-dimensional
SD	Spatially decaying
AGC-PI	Automatic gain control-proportional and integral
CMOS	complementary metal oxide semiconductor
D.R.C	disturbance rejection capability
CNS	Central Nervous System
UCM	uncontrolled manifold hypothesis
RF	Radio frequency
RLC	Repetitive Learning Control
ADC	Analog to digital converter
PWM	Pulse width modulator
DC	Direct current
LTI	linear time invariant
RPM	Round Per Mint

Chapter One

Introduction

Chapter One

Introduction

1.1 Introduction

Micro electromechanical systems (MEMS) (also written as micro-electro-mechanical, Micro electrochemical or microelectronic and micro electromechanical systems and the related micro mechatronics) is the technology of very small devices; it merges at the nano-scale into nano electromechanical systems (NEMS) and nanotechnology. MEMS are also referred to as micro machines (in Japan), or micro systems technology – MST (in Europe).

MEMS are separate and distinct from the hypothetical vision of molecular nano technology or molecular electronics. MEMS are made up of components between 1 to 100 micrometers in size (i.e. 0.001 to 0.1 mm), and MEMS devices generally range in size from 20 micrometers (20 micro of a meter) to a millimeter (i.e. 0.02 to 1.0 mm). They usually consist of a central unit that processes data (the microprocessor) and several components that interact with the surroundings such as micro sensors. At these size scales, the standard constructs of classical physics are not always useful. Because of the large surface area to volume ratio of MEMS, surface effects such as electrostatics and wetting dominate over volume effects such as inertia or thermal mass [1-3].

The MEMS technology based on a feedback control theory used mainly for stabilization and the control theory can be defined an interdisciplinary branch of engineering and mathematics that deals with the behavior of dynamical systems with inputs, and how their behavior is modified by feedback. The usual objective of control theory is to control a system, often called the plant, so its output follows a desired control signal, called the reference, which may be a fixed or changing value. To do this a controller is designed, which monitors the output and compares it with the reference. The difference between actual and desired output, called the error signal, is applied as feedback to the input of the system, to bring the actual output closer to the reference. Some topics studied in control theory are stability; whether the output will converge to the reference value or oscillate about it; controllability and observability.

Extensive use is usually made of a diagrammatic style known as the block diagram. The transfer function, also known as the system function or network function, is a mathematical representation of the relation between the input and output based on the differential equations describing the system.

Although a major application of control theory is in control systems engineering, which deals with the design of process control systems for industry, other applications range far beyond this. As the general theory of feedback systems, control theory is useful wherever feedback occurs; a few examples are in physiology, electronics, climate modeling, machine design, ecosystems, navigation, neural networks, predator-prey interaction, and gene expression [4].

The control system can be classified into three major topics

1- Linear systems control

2- Nonlinear systems control

3- Decentralized systems

1- Liner system control

For MIMO systems, pole placement can be performed mathematically using a state space representation of the open-loop system and calculating a feedback matrix assigning poles in the desired positions. In complicated systems this can require computer-assisted calculation capabilities, and cannot always ensure robustness. Furthermore, all system states are not in general measured and so observers must be included and incorporated in pole placement design.

2- Nonlinear systems control

Processes in industries like robotics and the aerospace industry typically have strong nonlinear dynamics. In control theory it is sometimes possible to linearize such classes of systems and apply linear techniques, but in many cases it can be necessary to devise from scratch theories permitting control of nonlinear systems. These e.g., feedback linearization, back-stepping, sliding mode control, trajectory linearization control normally take advantage of results based on Lyapunov's theory. Differential geometry has been widely used as a tool for generalizing well-known linear control concepts to the non-linear case, as well as showing the subtleties that make it a more challenging problem [4].

3- Decentralized systems

When the system is controlled by multiple controllers, the problem is one of decentralized control. Decentralization is helpful in many ways, for instance, it helps control systems operate over a larger geographical area. The agents in decentralized control systems can interact using communication channels and coordinate their actions.

1.2 Problem Definition

Existing technology before MEMS has the following problems

1- Increased weight and volume.

2- Increased power consumption

3- Increase design area.

4- Variation of the supply and movement represented in Non-stability could damage the system.

1.3 Objectives

1.3.1 General objectives

To design and simulate a closed loop control system of micro-electromechanical beam based on Matlab in order to investigate the stability of the MEMS system with a variation of forces.

1.3.2 Specific objectives

1- Design of linking blocks.

2- Wiring the system blocks.

3- Configuring the simulation environment.

4- Run simulation.

5- Obtain results.

1.4 Methodology

Descriptive analysis and simulation of micro electromechanical system using Matlab Simulink.

1.5 Thesis layout

This study includes five chapters, in chapter one an introduction of closed loop control of micro-electromechanical beam including problem definition, objectives and the methodology used, while chapter two represents the literature reviews including papers, while chapter three includes the methodology, in chapter four the simulation with results and discussion is written and finally in chapter five the conclusion and recommendation is written.

Chapter Two

Literature Review

Chapter Two

Literature Review

2.1 Stability Enhancement by Boundary Control in 2-D channel flow

Andros Balogh et al discusses Control of a viscous incompressible fluid flow in a two dimensional (2-D) channel to stabilize the parabolic equilibrium profile in a two-dimensional (2-D) channel flow.

The control of channel flow was previously considered by Speyer and Coworkers, and Bewley and coworkers, who derived feedback laws based on linear optimal control, and implemented by wall-normal actuation. With an objective to achieve stability , we arrive at a feedback law using tangential actuation (using teamed pairs of synthetic jets or rotating disks) and only local measurements of wall shear stress, allowing to embed the feedback in micro- electromechanical systems (MEMS) hardware, without need for wiring .

The theoretical results are limited to low values of Reynolds number; however, they present simulations that demonstrate the effectiveness of the proposed feedback for values five order of magnitude higher [5].

2.2 Reconfigurable Closed - Loop Digital ΔΣ Capacitive MEMS Accelerometer for Wide Dynamic Range, High Linearity Applications

Chao Wang et al present a 4th order ΔΣ closed-loop system with a digital 2nd order ΔΣ modulator.

The digital ΔΣ modulator allows fine accuracy in choosing the coefficients for the ΔΣ modulators. It also provides flexibility in the placement of poles and zeros for compensating the unforeseen phase delays caused by fabrication non-idealities by using Electrostatic force feedback. The feedback force balances the sensor structure around its nominal position through electrostatic feedback. Thus, the feedback force becomes a measure of the externally applied force with high linearity.

The digital implementation of ΔΣ modulator allows us to build reconfigurable closed-loop system with the potential for even higher order system which can be optimized to suit different MEMS sensor characteristics and performance [6].

2.3 Optimal Control of Spatially Distributed Systems

The structural properties of optimal control of spatially distributed systems with infinite-horizon linear quadratic criteria studied by Nader Motee and Ali Jadbabaie, Such systems consist of an infinite collection of possibly heterogeneous linear control systems that are spatially interconnected via certain distant-dependent coupling functions over arbitrary graphs, by analyzing the spatial structure of the solution to the corresponding operator Lyapunov and Riccati equations. The key idea of the paper is the introduction of a special class of operators called spatially decaying (SD).

They prove that given a control system with a state-space representation consisting of SD operators. Furthermore, they show that the kernel of the optimal state feedback for each subsystem decays in the spatial domain, with the type of decay (e.g, exponential, polynomial or logarithmic) depending on the type of coupling between subsystems [7].

2.4 Analysis and Design of a 3rd Order Velocity-Controlled Closed-Loop for MEMS Vibratory Gyroscopes

analyzing the specific performance of the automatic gain control-proportional and integral (AGC-PI) based velocity-controlled closed-loop in a micro-electro-mechanical systems (MEMS) vibratory gyroscope by a linearization design approach to overcome this limitation by establishing a 3rd order linear model of the control loop and transferring the analysis to the frequency domain[8].

Closed-loop drive circuits are designed and implemented using 0.35μm complementary metal oxide semiconductor (CMOS) process, and experiments carried out on a gyroscope prototype verify the optimization methodology that an optimized stability of the control loop can be achieved by constructing the zero-pole doublet, and disturbance rejection capability (D.R.C) of the control loop can be improved by increasing the integral term.

2.5Demonstrating sub-nm closed loop MEMS flattening

Ground based high-contrast imaging (e.g. extra solar giant planet detection) has demanding wave front control requirements two orders of magnitude more precise than standard adaptive optics systems.

J.Evans, B.Macintosh, L.Poyneer, S. Severson, D. Dillon, D.Gavel, L.Reza Were demonstrate that these requirements can be achieved with a 1024-Micro- Electrical-Mechanical-Systems (MEMS) deformable mirror having an actuator spacing of 340 m and a stroke of approximately 1m, over an active aperture 27 actuators across.

They have flattened the mirror to a residual wave front error of 0.54 nm rms within the range of controllable spatial frequencies [9].

2.6 Cantilever-based electret energy harvesters

In [10] presented electrostatic converters using electrets by using converters able to turn mechanical energy, such as vibrations, into electricity.

They develop an accurate analytical model of a simple but efficient cantilever-based electret energy harvester. They prove that with vibrations of 0.1g (1 m s−2), it is theoretically possible to harvest up to 30 μWper gram of mobile mass. This power corresponds to the maximum output power of a resonant energy harvester according to the model of William and Yates.

Simulation results are validated by experimental measurements, raising at the same time the large impact of parasitic capacitances on the output power. Therefore, they 'only' managed to harvest 10 μW per gram of mobile mass, but according to our factor of merit, this is among the best results so far achieved.

2 .7 Closed-loop Control of a Novel 2-DOF MEMS Nanopositioner with Electrothermal Actuation

Anthony, Mickey and S.O. Reza used Z-shaped electrothermal actuators to position the device's central stage. The design of the Z-shaped beams used in the presented device allows two actuators to be coupled back-to-back to achieve bidirectional motion along each of the two axes. Testing of the device shows that stage displacements in excess of ±5 μm are achievable for both the x and y axes. The device features integrated displacement sensors based on poly silicon electrothermal heaters, which are supplied with an electrical bias voltage that results in Joule heating. The resistance of each heater varies depending on the position of the central stage, with two heaters being used per axis in a differential configuration. The displacement measurements are utilized as part of an implemented closed-loop control scheme that uses both feed forward and feedback mechanisms based on the principle of internal model control [11]

Chapter Three

Methodology

Chapter Three

Methodology

3.1 Introduction

In this research two case studies was chosen Repetitive Control of an electrostatic micro bridge actuator and the non-linear Control of MEMS, a simulation through matlab is done to the non-linear Control of MEMS to evaluate the performance of the systems and based on their structures using simulation software.

3.2 Non-linear Control of MEMS

Nonlinear control theory is the area of control theory which deals with systems that are nonlinear, time-variant, or both.

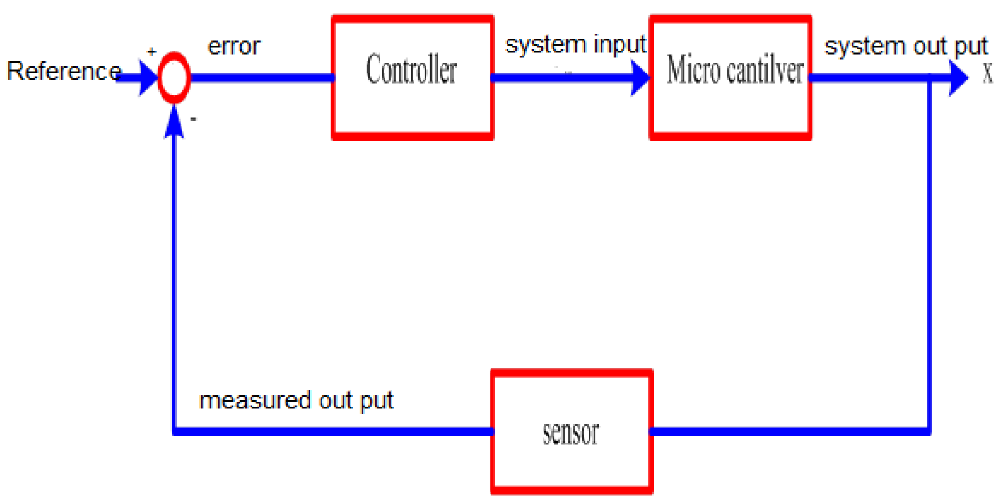

Figure (3.1) closed loop control system [4]

A feedback control system. It is desired to control a system (often called the plant) so its output follows a desired reference signal. A sensor monitors the output and a controller subtracts the actual output from the desired reference output, and applies this error signal to the system to bring the output closer to the reference. In a nonlinear control system at least one of the blocks, system, sensor, or controller, is nonlinear.

Control theory is an interdisciplinary branch of engineering and mathematics that is concerned with the behavior of dynamical systems with inputs, and how to modify the output by changes in the input using feedback. The system to be controlled is called the "plant". In order to make the output of a system follow a desired reference signal a controller is designed which compares the output of the plant to the desired output, and provides feedback to the plant to modify the output to bring it closer to the desired output. Control theory is divided into two branches:

Linear control theory applies to systems made of linear devices; which means they obey the superposition principle; the output of the device is proportional to its input. Systems with this property are governed by linear differential equations. A major subclass is systems which in addition have parameters which do not change with time, called linear time invariant (LTI) systems .These systems are amenable to powerful frequency domain mathematical techniques of great generality, such as the Laplace transform, Fourier transform, Z transform, root-locus, Bode plot, and Nyquist stability criterion. These lead to a description of the system using terms like bandwidth, frequency response, eigen values, gain, resonant frequencies, poles, and zeros, which give solutions for system response and design techniques to most problems of interest.

Nonlinear control theory covers a wider class of systems that do not obey the superposition principle. It applies to more real-world systems, because all real control systems are nonlinear. These systems are often governed by nonlinear differential equations. The mathematical techniques which have been developed to handle them are more rigorous and much less general, often applying only to narrow categories of systems. These include limit cycle theory, Poincare maps, Liapunov stability theory, and describing functions. If only solutions near a stable point are of interest, nonlinear systems can often be linearized by approximating them by a linear system obtained by expanding the nonlinear solution in a series, and then linear techniques can be used. Nonlinear systems are often analyzed using numerical methods on computers, for example by simulating their operation using a simulation language. Even if the plant is linear, a nonlinear controller can often have attractive features such as simpler implementation, faster speed, more accuracy, or reduced control energy, which justify the more difficult design procedure [4].

3.3 Method of the work:

Sources of nonlinearities in the MEMS cantilever system were the nonlinear electrostatic force and a separate nonlinear capacitive sensor by using multiple initial conditions.

In this work use two chips are bonded together to form a MEMS based non-volatile magnetic mass storage device see figure (3.2).

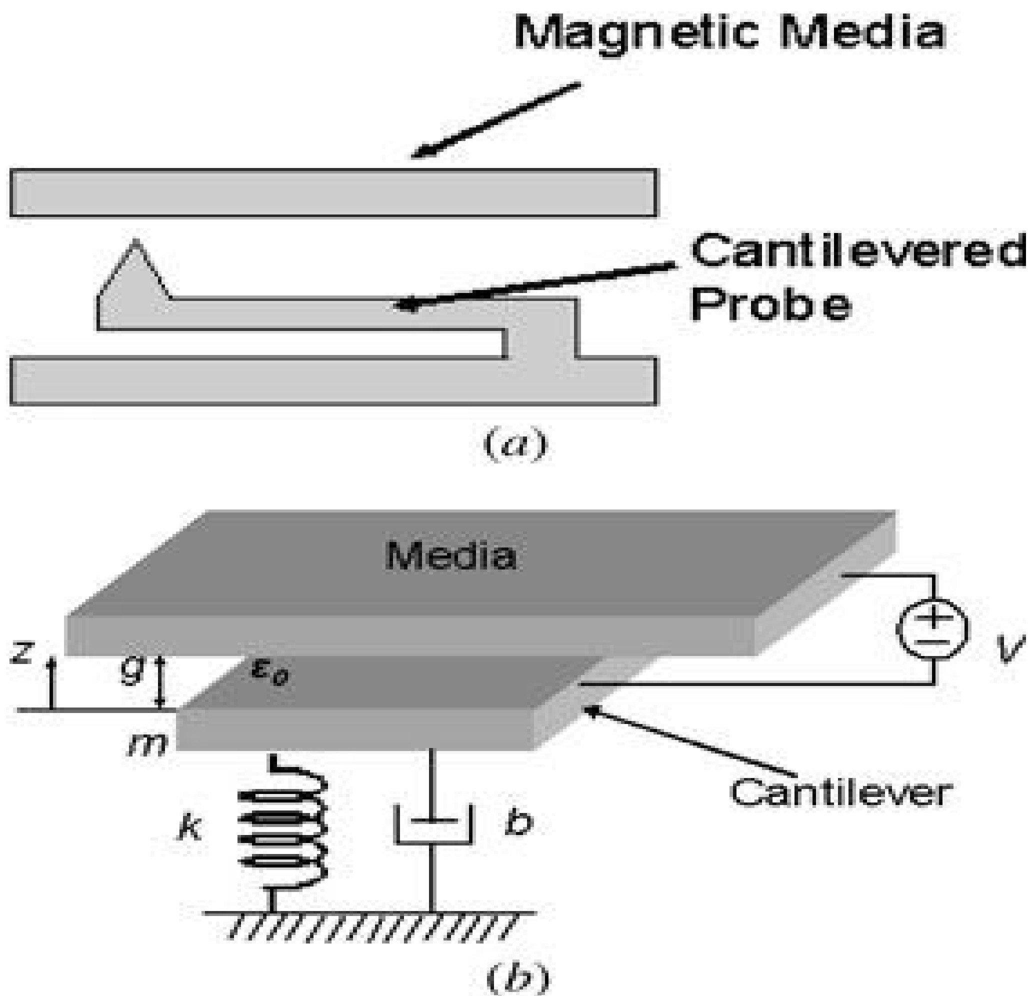

Figure (3.2) nonlinearities in the MEMS cantilever system [12]

The upper chip contains a moveable magnetic medium, which is addressed by an array of cantilevered probes illustrated on the bottom chip, produced the actuating voltage. The actuating force and the disturbance force are used to move the MEMS cantilever and produced the output, when the sensor's output voltage is measured and the discrepancy between the reference input voltage and sensor's output voltage is sent to the controller to process it [12].

3.4 Block Diagram

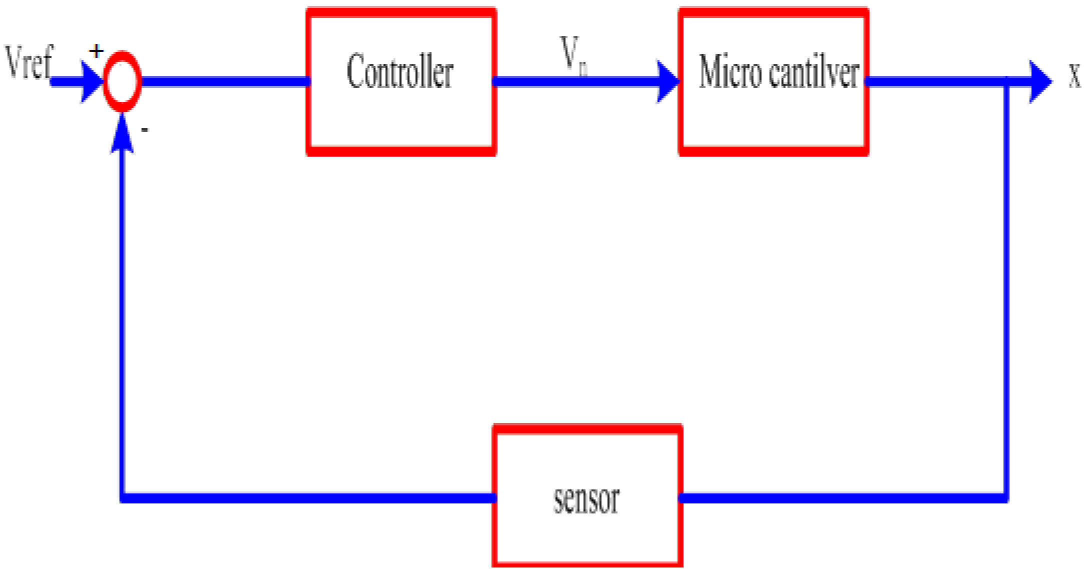

Figure (3.3) system block diagram

3.4.1Block diagram description

In the structure of the system includes reference voltage, controller produced the actuating voltage used to move the cantilever , mems and the block was updated with a sensor that has a feedback to apply a readjustment through a control circuit.

3.5 Mathematical model for nonlinear control

We use equation to investigate both the static and dynamic instability of the MEMS cantilever systems subjected to weak disturbances. We found bistability in the closed loop controlled cantilever [12].

3.5.1The equation of MEMS cantilever

$\ddot{x} + \gamma \cdot \dot{x} + x = V^2 / (1 - x)^2$ (3.1)

$x = \frac{z}{g}$ (3.2)

$\gamma = \frac{b}{mk}$ (3.3)

Where

$\dot{x}$ and $\ddot{x}$ are respectively the first- and second-order derivatives of x with respect to τ

$V_n = G(V_r - V_s)$ (3.4)

$V_s = K x / (h - x)$ (3.5)

$h = d/(d - 1)$ (3.6)

$d = Cc/Cs_0$ (3.7)

$K = KsVmod\sqrt{\varepsilon_0 A/2kg^3 / (d - 1)}$ (3.8)

Where

G: the controller gain

V_r: reference input voltage

V_s : Output voltage Sensor

d :ratio of the parasitic capacitance over the initial sensor capacitance.

h:parameter affected by the parasitic capacitance and the initial sensor capacitance

K :gain of the sensor

Ks:gain amplifier

Vmod: input of the sensor amplifier

A: $area$

1-bi-stablity

Bi-stability occurs for rang of x before the cantilever snap close at x >0.9 . We use equations (3.1),(3.4)and (3.5) with equation (3.9) to investigate the stability of the cantilevers .

$$Vs' = -r\left(vs - \frac{kx}{1-x}\right) \qquad (3.9)$$

r : bandwidth of the low pass filter

γ=0.7

h=1

k=0.06

G=1

Vr=0.405

r=10

2- Instability of the cantilever system subjected to a small sinusoidal disturbance

Investigate the dynamic stability of the cantilever system subjected to weak disturbances with magnitude (an) much less than the magnitude of the electrostatic force. So the state space representation of the closed loop controlled cantilever system subjected to disturbances is given by the following normalized equations:

$$y' = -\gamma y - x + G^2 \frac{(vr-vs)^2}{(1-x)^2} + an\cos(\Omega T) \qquad (3.10)$$

$$\Omega = \frac{\omega}{\omega 0} \qquad (3.11)$$

$$\omega_o = k/m \qquad (3.12)$$

$\tau = \omega_o\, t$

ω_o:cantilever's natural frequency

τ : normalized time

γ=0.7

h=1

k=o.o83

G=2.4

r =10

Vr =0.35

an =o.o01

ω =314

3.6 Repetitive control

Repetitive Control is a control method it is based on the Internal Model Principle and used specifically in dealing with periodic signals.

3.6.1Internal model (motor control)

In the subject area of motor control, an internal model is a postulated neural process that simulates the response of the motor system in order to estimate the outcome of a motor command.

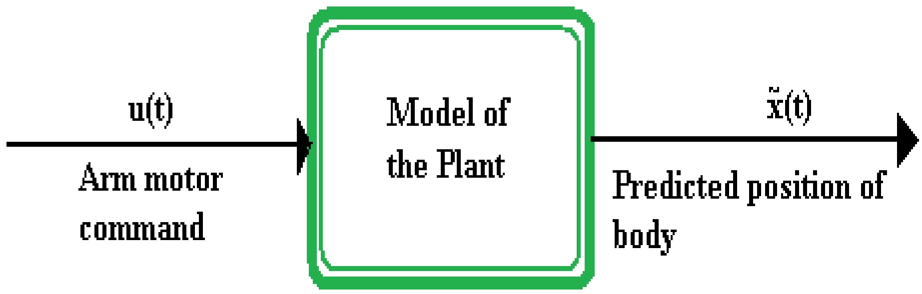

Figure (3.4) Forward model of an arm movement [14]

The internal model theory of motor control argues that the motor system is controlled by the constant interactions of the “plant” and the “controller” The plant is the body part being controlled, while the internal model itself is considered part of the controller. Information from the controller, such as information from the CNS, feedback information, and the reference copy, is sent to the plant which moves accordingly.

Internal models can be controlled through either feed-forward or feed back control. Feed-forward control computes its input into a system using only the current state and its model of the system. It does not use feedback, so it cannot correct for errors in its control. In feedback control, some of the output of the system can be fed back into the system's input, and the system is then able to make adjustments or compensate for errors from its desired output. Two primary types of internal models have been proposed: forward models and inverse models. In simulations, models can be combined together to solve more complex movement tasks [13-15].

1- Forward models

Motor command is sent to the plant to move the body and a reference copy of the motor command is sent to a forward model. The output from the forward model (predicted body position) is compared with the output from the plant (body position). Noise from the system or the environment may cause differences between the actual and predicted body positions. The error (difference) between the actual and predicted positions can provide feedback to improve the movement for the next iteration of the internal model.

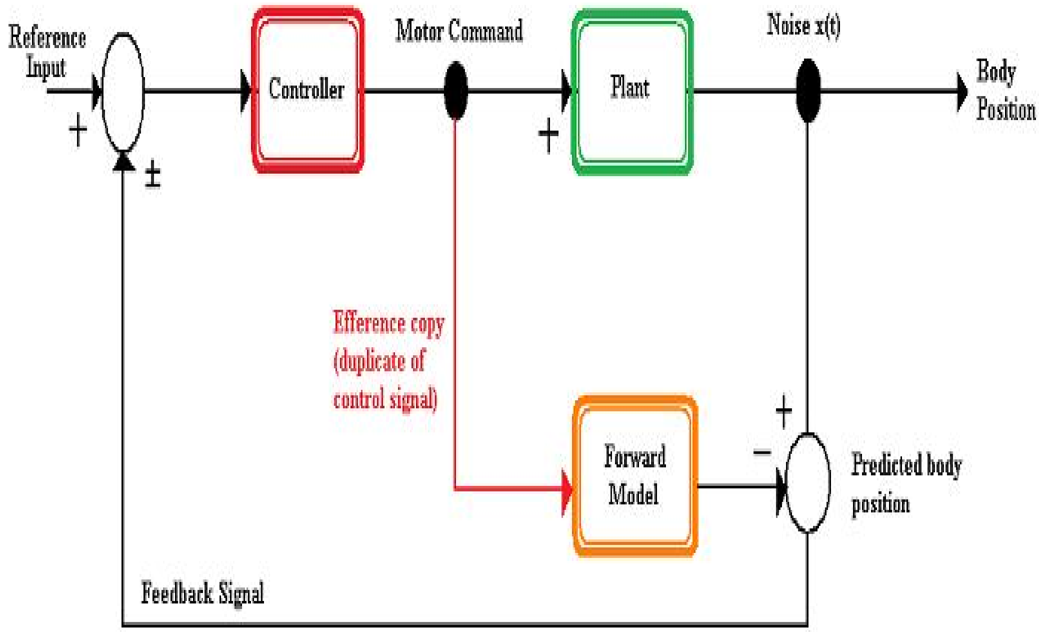

Figure (3.5) motor command [14]

In their simplest form, forward models take the input of a motor command to the “plant” and output a predicted position of the body.

The motor command input to the forward model can be a reference copy, as seen in Figure (3.5). The output from that forward model, the predicted position of the body, is then compared with the actual position of the body. The actual and predicted position of the body may differ due to noise introduced into the system by either internal (e.g. body sensors are not perfect, sensory noise) or external (e.g. unpredictable forces from outside the body) sources. If the actual and predicted body positions differ, the difference can be fed back as an input into the entire system again so that an adjusted set of motor commands can be formed to create a more accurate movement.

2- Inverse models

Inverse models use the desired and actual position of the body as inputs to estimate the necessary motor commands which would transform the current position into the desired one.

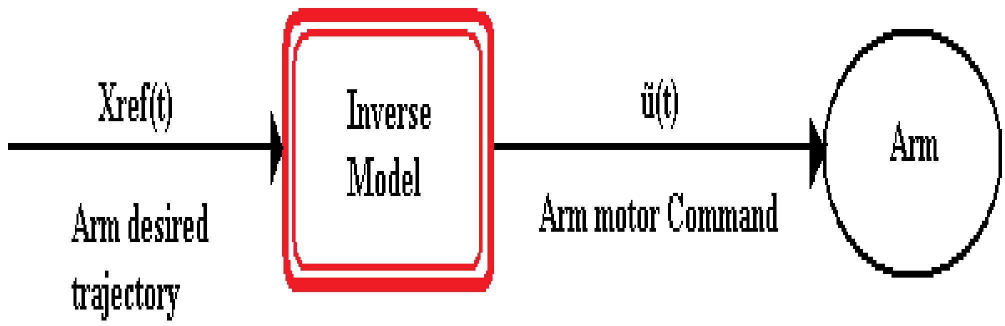

Figure (3.6) Inverse model of a reaching task [14]

For example, in an arm reaching task, the desired position (or a trajectory of consecutive positions) of the arm is input into the postulated inverse model, and the inverse model generates the motor commands needed to control the arm and bring it into this desired configuration (Figure 3.6). Inverse internal models are also in close connection with the uncontrolled manifold hypothesis (UCM) .

3- Combined forward and inverse models

Theoretical work has shown [13-15] that in models of motor control, when inverse models are used in combination with a forward model, the reference copy of the motor command output from the inverse model can be used as an input to a forward model for further predictions. For example if, in addition to reaching with the arm, the hand must be controlled to grab an object, an reference copy of the arm motor command can be input into a forward model to estimate the arm's predicted trajectory. With this information, the controller can then generate the appropriate motor command telling the hand to grab the object. It has been proposed that if they exist, this combination of inverse and forward models would allow the CNS to take a desired action (reach with the arm), accurately control the reach and then accurately control the hand to grip an object.

3.6.2 Adaptive Control theory

With the assumption that new models can be acquired and pre-existing models can be updated, the reference copy is important for the adaptive control of a movement task. Throughout the duration of a motor task, a reference copy is fed into a forward model known as a dynamics predictor whose output allows prediction of the motor output .When applying adaptive control theory techniques to motor control, reference copy is used in indirect control schemes as the input to the reference model.

3.6.3 Repetitive Learning Control of MEMS

Repetitive Learning Control is applied to an electrostatic micro bridge and a repetitive contact imager. Electrostatic micro actuators are used extensively in MEMS sensors, RF switches, and micro fluidic pumps. Due to high bandwidth operation, however, reduction of residual vibration using feedback control is difficult to implement. Feed forward

RLC is designed, proven stable, and simulated for an electrostatic micro bridge under a periodic desired spatial/time trajectory. High residual stresses in the micro bridge mean that bending stiffness can be neglected and a pinned string model with uniform loading is appropriate.

Offline RLC processing of the average displacement as measured by capacitive sensing updates a waveform generator's parameters [16].

3.7 Method of the work

Figure (3.7) shown the work of the micro bridge actuator. The micro bridge can vibrate transversely with a displacement w(x,t),where x is the spatial position and time by using the actuation voltage .

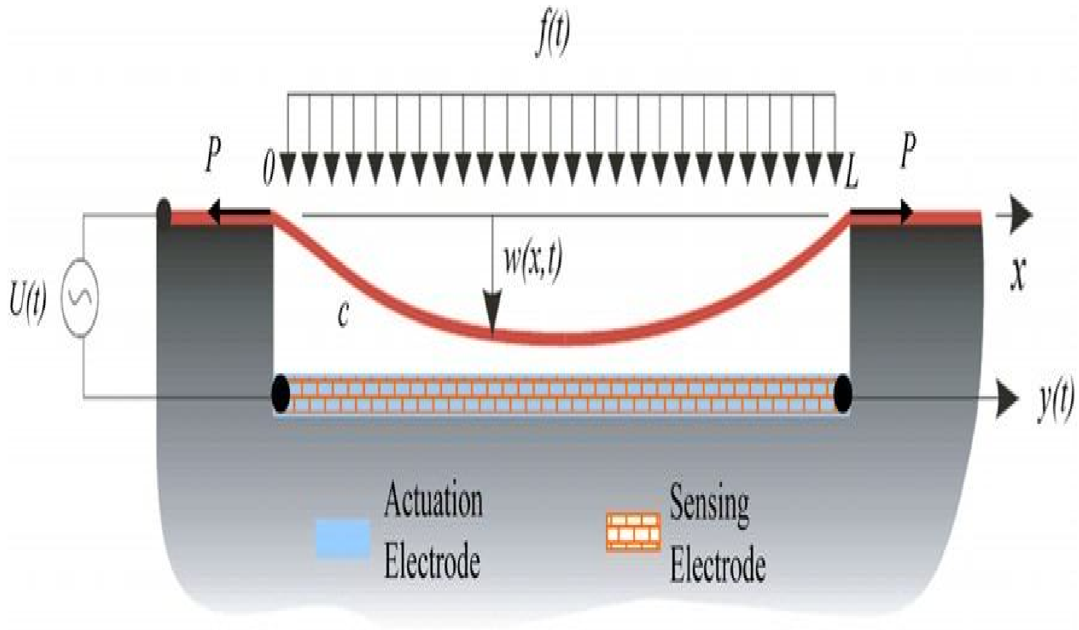

Figure (3.7) Schematic diagram of the electrostatic micro bridge model

The actuation voltages produced by a wave form generator that is periodically triggered with sample period of T. And produces the measured time responsey (t) The output is measured by the capacitive sensing and

buffered in the high speed analog to digital converter(ADC). Block of sampled ADC data is loaded in to the control microprocessor(feed forward controller)every TR seconds. The repetitive algorithm is implemented on this microprocessor and used to update the wave form generator voltage trajectory. The output Iterative until access to the Actual output for the micro bridge displacement[17].

3.8 Block diagram

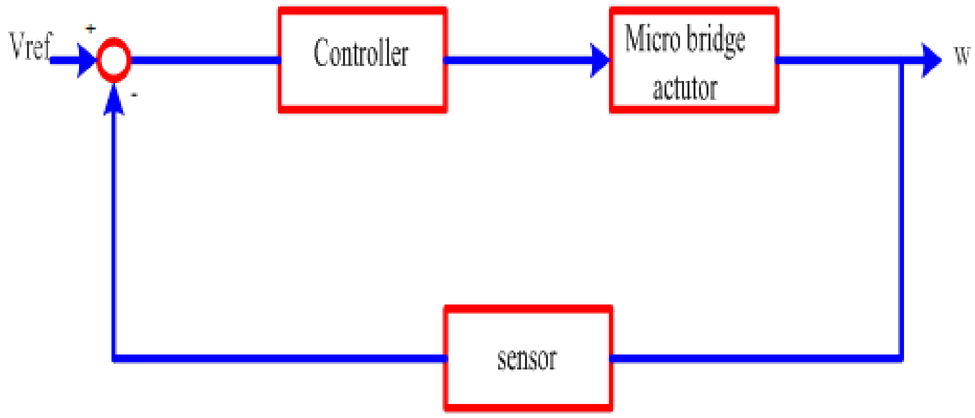

Figure (3.8) Repetitive control block diagram

3.8.1 Repetitive Control Block Diagram Description

The Repetitive Control system block diagram consists of a reference voltage, controller, micro bridge actuator and sensor that have a feedback to apply a readjustment through a control circuit[17].

3.9 Mathematical model for repetitive control system

The field equation and boundary conditions are

$$\rho\ddot{w} + c\dot{w} - Pwxx = f \quad (3.13)$$

$$w(0,t) = w(L,t) = 0$$

Where

ρ: mass/length

P: residual tension

L:the length

C: viscous damping coefficient

f (t): uniformly distributed electrostatic force

Dots and the subscript x: indicate partial differentiation with respect to time, t, and space, x.

$$e(x, t) = \upsilon(x, t) - w(x, t) \quad (3.14)$$

$$\upsilon(0, t) = \upsilon(L, t) = 0$$

e(x, t) :distributed response error

υ(x, t): desired shape and time trajectory

The transformed equations:

$$\rho e'' + c e' - P e_{xx} = q - f \quad (3.15)$$

$$e(0, t) = e(L, t) = 0$$

$$q(X, t) = \rho\upsilon'' + c\upsilon - P\upsilon_{xx} \quad (3.16)$$

$$q_e(t) = \int_0^1 (\beta_s e' + \beta_c e)dx \quad (3.17)$$

Chapter Four

Simulation and result discussion

Simulation and result discussion

4.1 Introduction

In simulations use one case study by using Matlab software (nonlinear control of MEMS), the simulation was done using block sets by Simulink, results was obtained and discussed in this chapter.

4.2 Simulation of nonlinear closed loop control (bi stability)

The following simulation illustrates the nonlinearity of the MEMS and the closed loop control effects on the system. The system is consisting of a reference voltage that used for supply the system. Also the reference voltage is connected to the controller that produced the actuating voltage was used to move the MEMS cantilever and produced the output, that can be monitored through a sensor , When the sensor's output voltage is measured and the discrepancy between the reference input voltage and sensor's output voltage is sent to the controller to process it . Repeated until investigate the stability of the cantilever See figure (4.1).

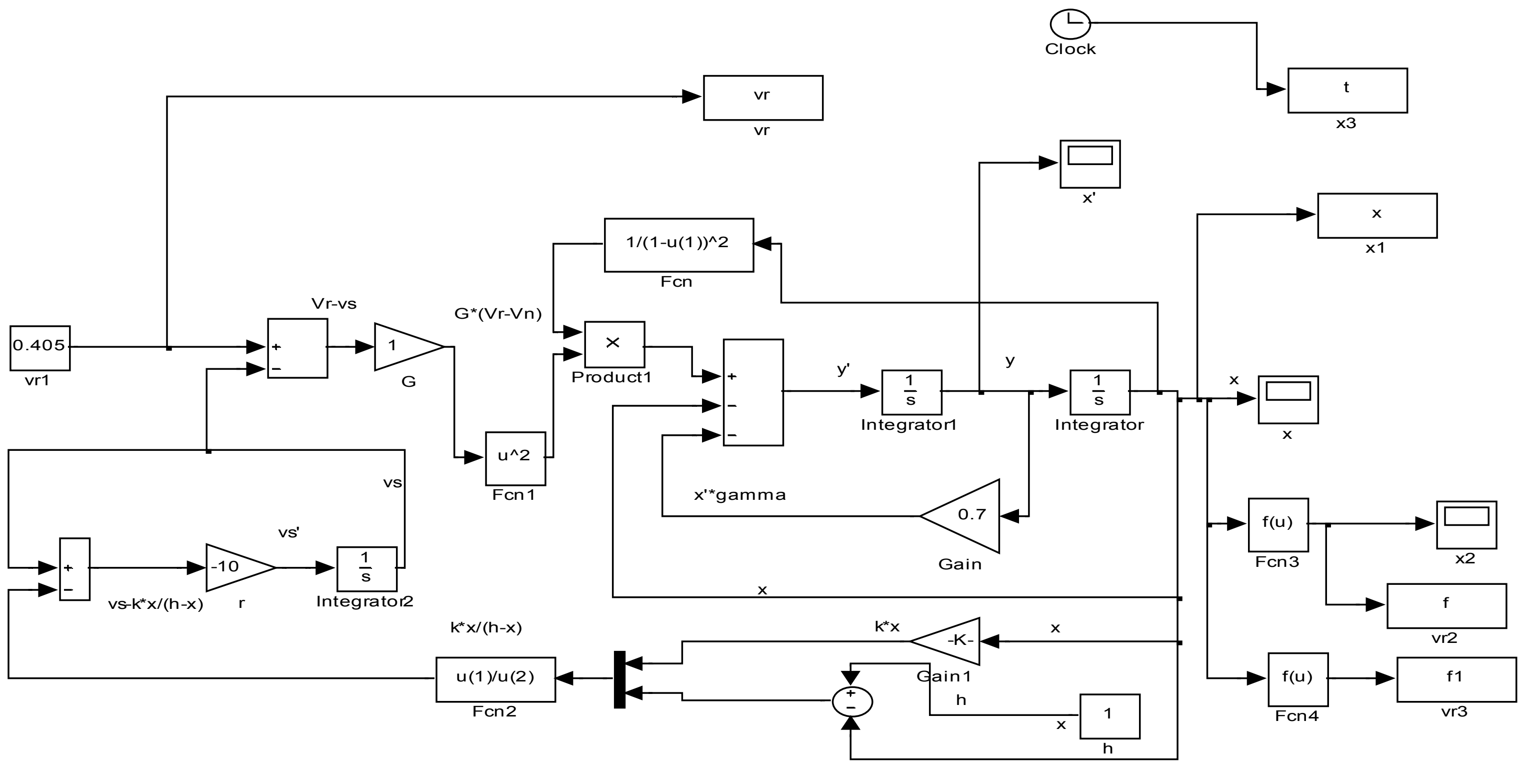

Figure (4.1) nonlinear control block set(bi-stablity)

4.3 Simulation of nonlinear closed loop control (small sinusoidal disturbance)

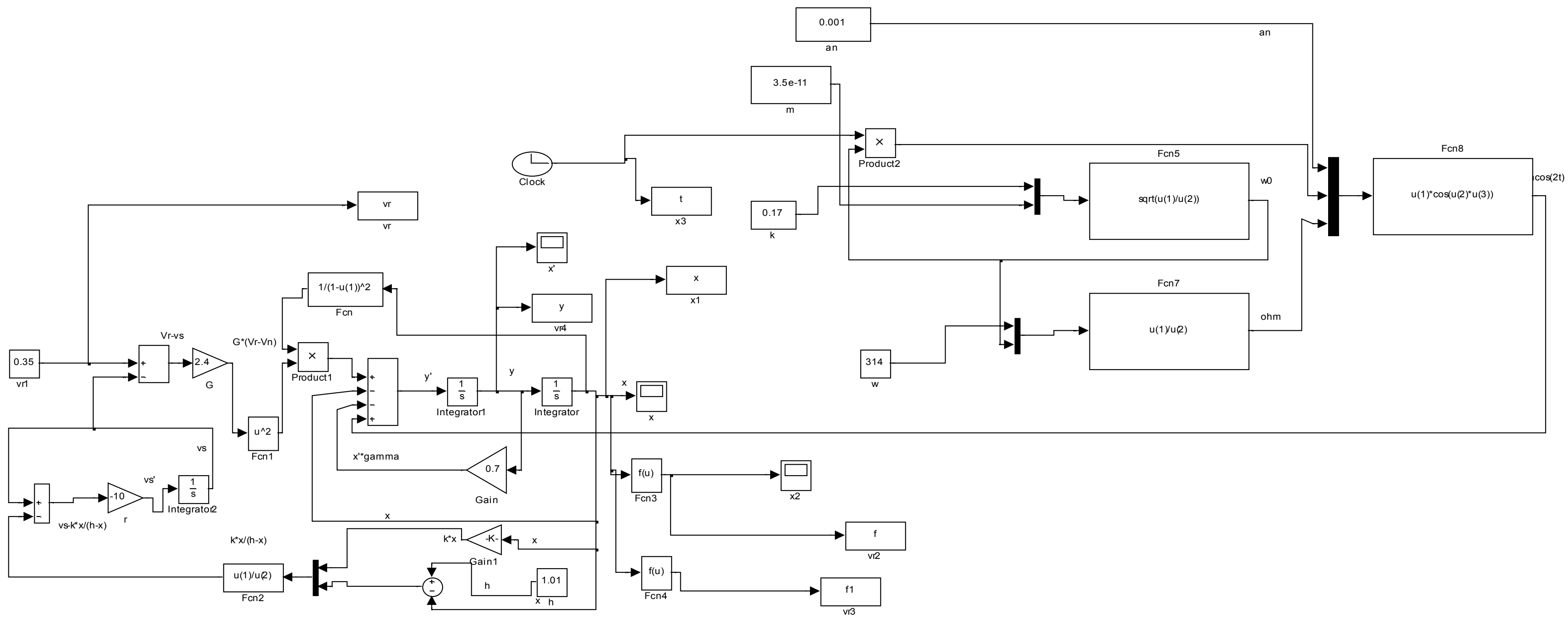

Figure (4.2) nonlinear control block set (small disturbance)

4.4 Results and Discussion nonlinear (bi stability)

4.4.1 Time vs. Simulation spatial position

While running the simulation of the system it was found increasing through the simulation time from 0 to 6 (simulation time) and from 0 to 0.34(spatial position),from 6 to10 is decrease and from 10 to 19.5 of simulation time the variation was discrete and from 19.5 to end it was investigate the stability of the cantilever at spatial position (0.2826).See figure (4.3)

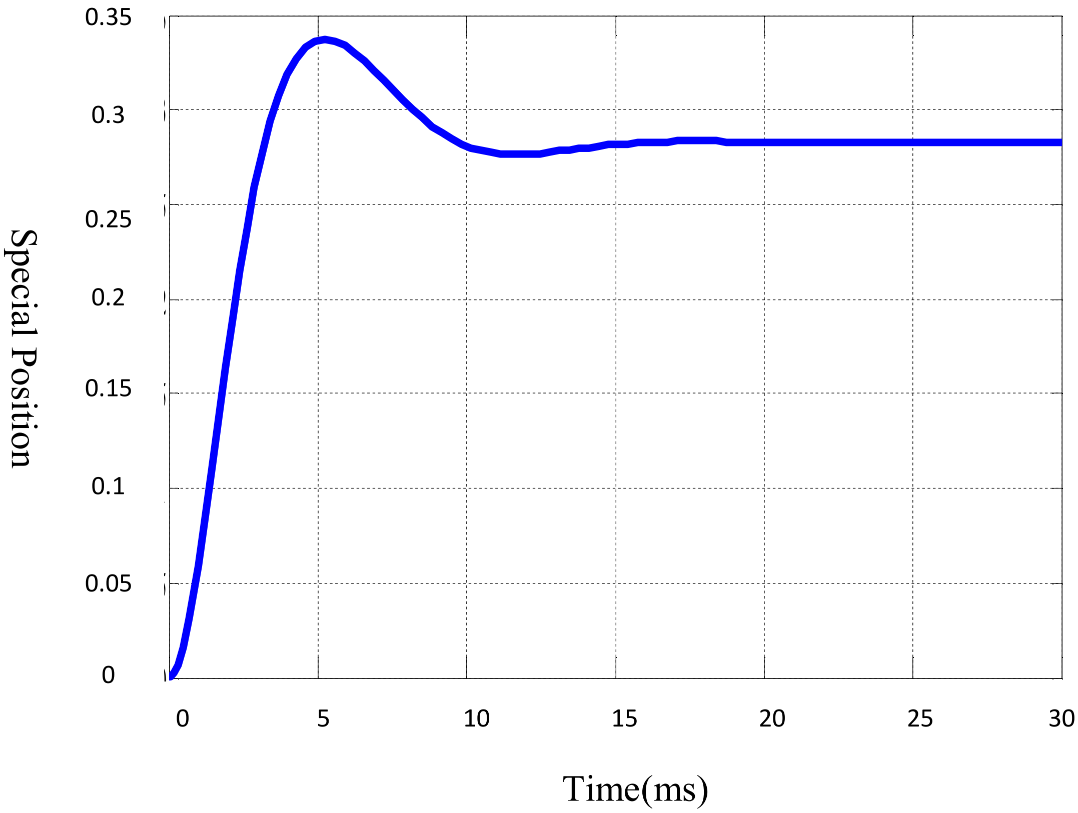

Figure (4.3)Time vs. Simulation spatial position

4.4.2 Time vs. Simulation frequency

When starting the simulation of the system it increase the simulation time from 0 to 2.5 (simulation time) and from 0 to 0.28(frequency),from 2.5 to5 is decrease also from 5 to 10 of simulation time is increase and from10 to 21 was discrete and from 21 to end it was investigate the stability of the cantilever at frequency (0.2736).See figure (4.4)

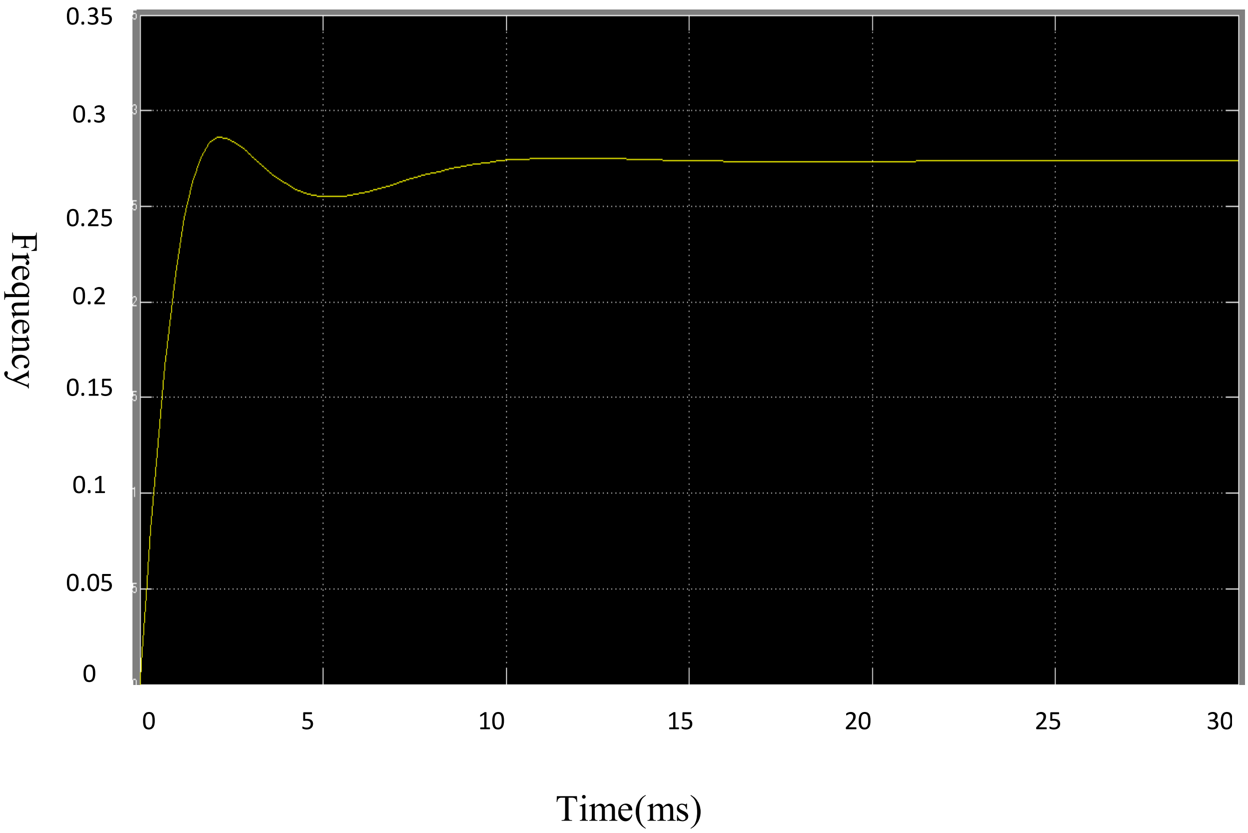

Figure (4.4) Simulation Time vs. frequency

4.4.3 Spatial position vs. Simulation reference voltage

When the starting of the simulation the reference voltage is 0.405 in all of the simulation .See figure (4.5)

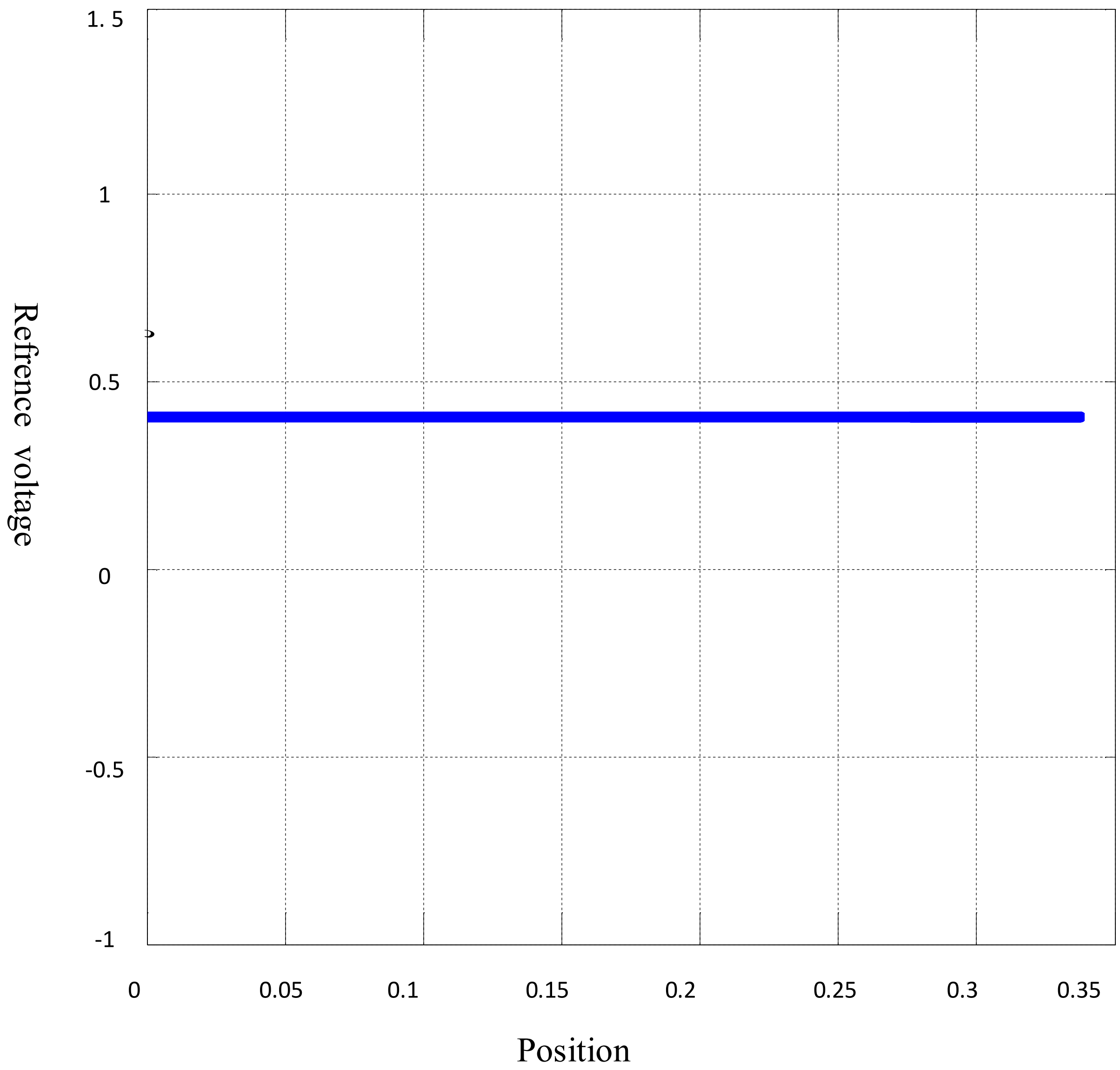

Figure (4.5) spatial position vs. Simulation reference voltage

4.4.4 Spatial position vs. Simulation frequency (f)

When starting the simulation of the system it increase the spatial position from 0 to 0.18, from 0.18 to0.22 is stable at frequency (0.2736).But also is decrease from 0.22 to end of simulation. See figure (4.6)

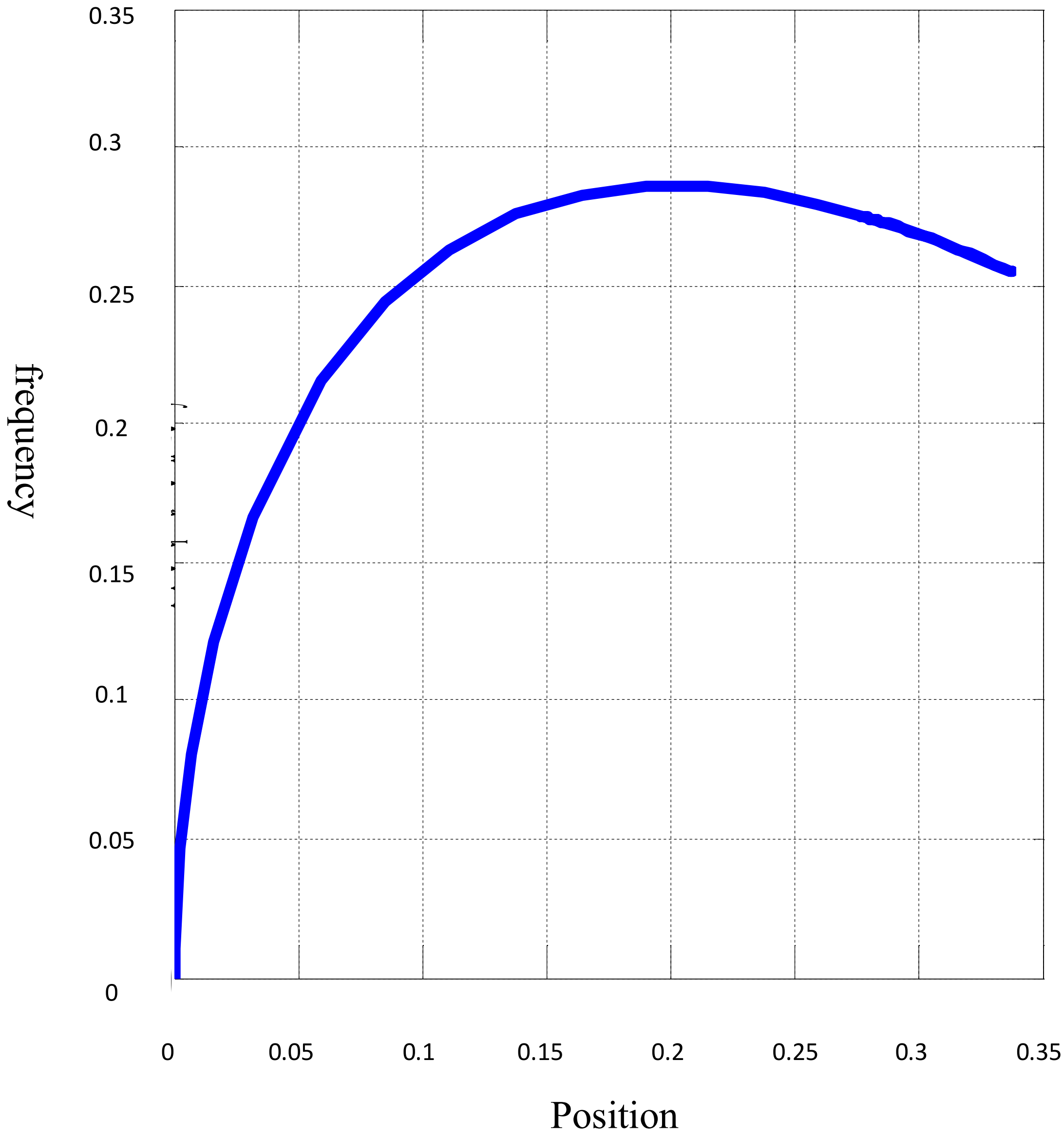

Figure (4.6) spatial position vs. Simulation frequency(f)

4.4.5 Spatial position vs. Simulation frequency

In this simulation the frequency of the system is the same and is stable at (0.2736)from 0.18 to0.22(spatial position) and also is decrease from 0.22 to end of the simulation system. See figure (4.7)

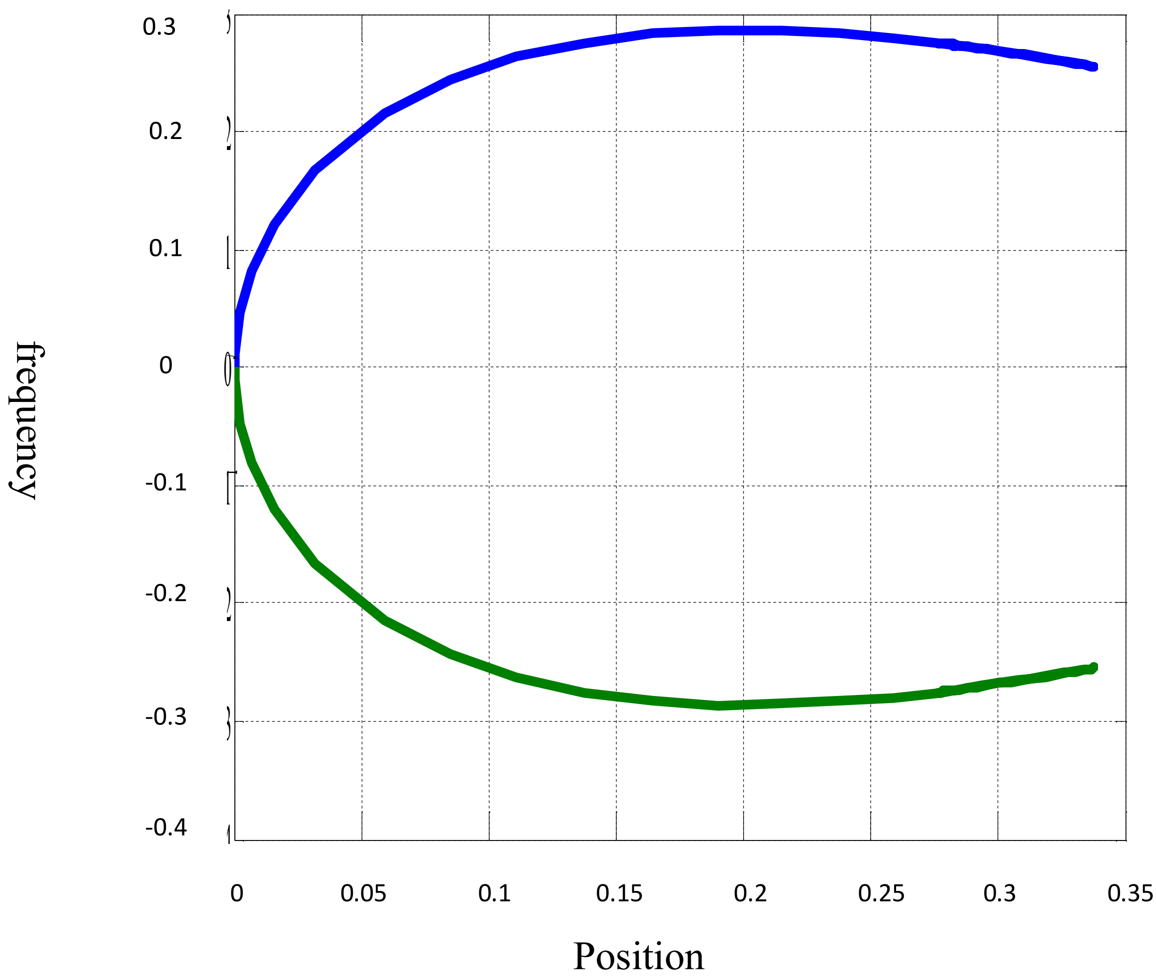

Figure (4.7) spatial position vs. Simulation frequency

4.4.6Table of Bi-stability reading descriptions

NO	Items	Reading
1	Rise time	0.495
2	Peak time	0.435
3	Max overshoot	2.0332e+5
4	Settling time	0.495
5	Actual position	0.2826

Table(4.1) for bi-stability reading

4.5 Results and Discussion nonlinear (small sinusoidal disturbance)

4.5.1 Time vs. Simulation spatial position

While running the simulation of the system the cantilever stable at spatial position (0)from 0 to 2 (simulation time) but it change by increasing the spatial position to (13) and decreasing to x equal (6) approximately and also it decrease and increase until stable at x equal zero, in this position investigated the stability of the cantilever .See figure (4.8)

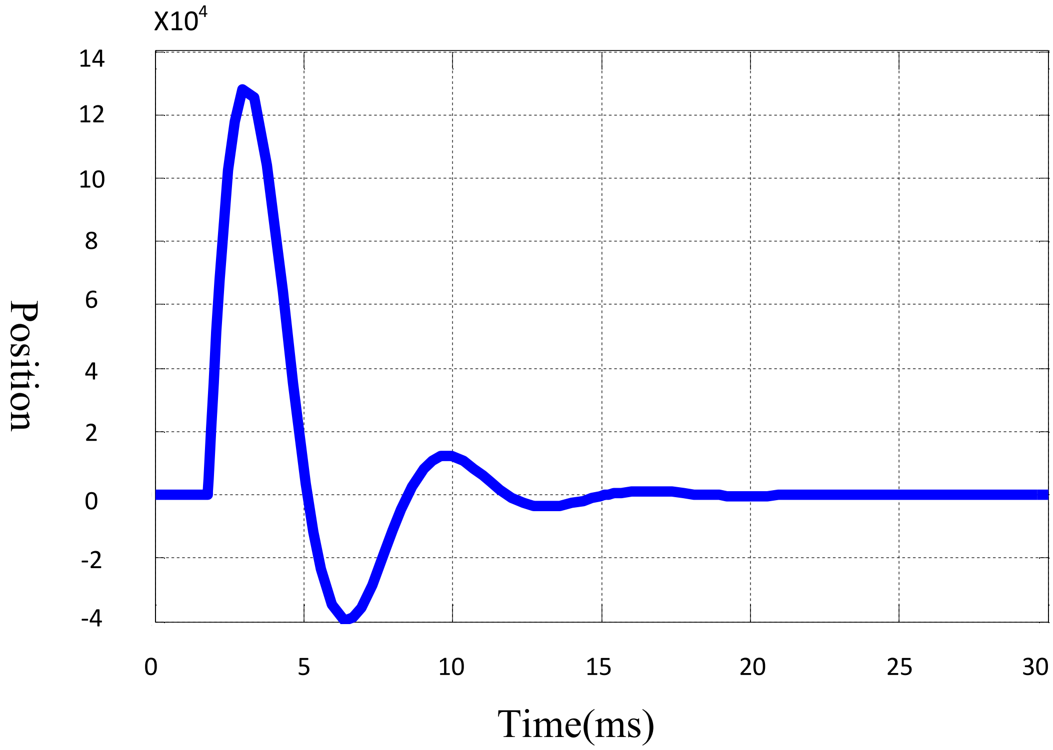

Figure (4.8)Time vs. Simulation spatial position

4.5.2 Spatial position vs. Simulation reference voltage

When the starting of the simulation the reference voltage is 0.35 (constant) in all of the simulation .See figure (4.9)

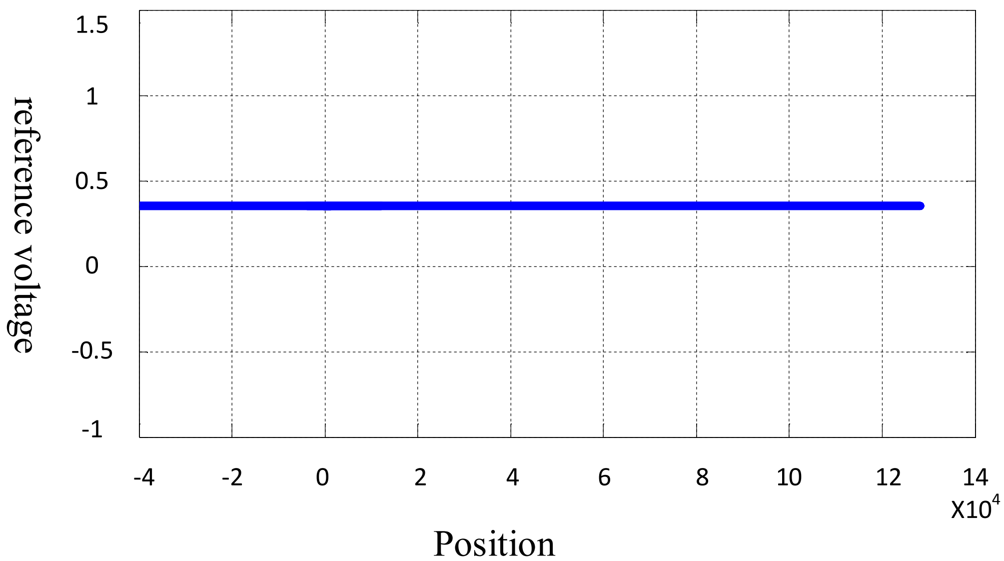

Figure (4.9) spatial position vs. Simulation reference voltage

4.5.3 Spatial position vs. Simulation frequency (f)

When starting the simulation of the system it increase the spatial position and frequency stable at zero and it also increase. See figure (4.10)

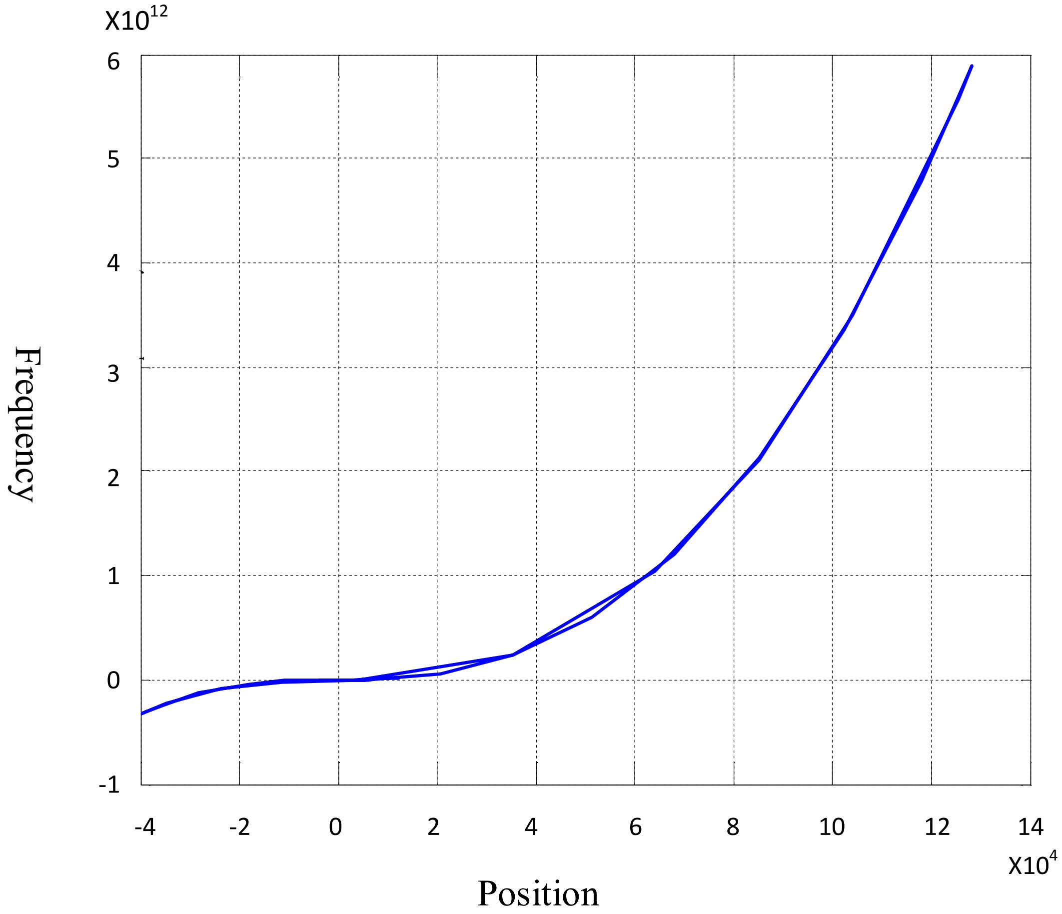

Figure (4.10) spatial position vs. Simulation frequency

4.5.4 Spatial position vs. Simulation frequency (f1)

When starting the simulation of the system it decrease the spatial position and frequency stable at zero and it also decrease. See figure (4.11)

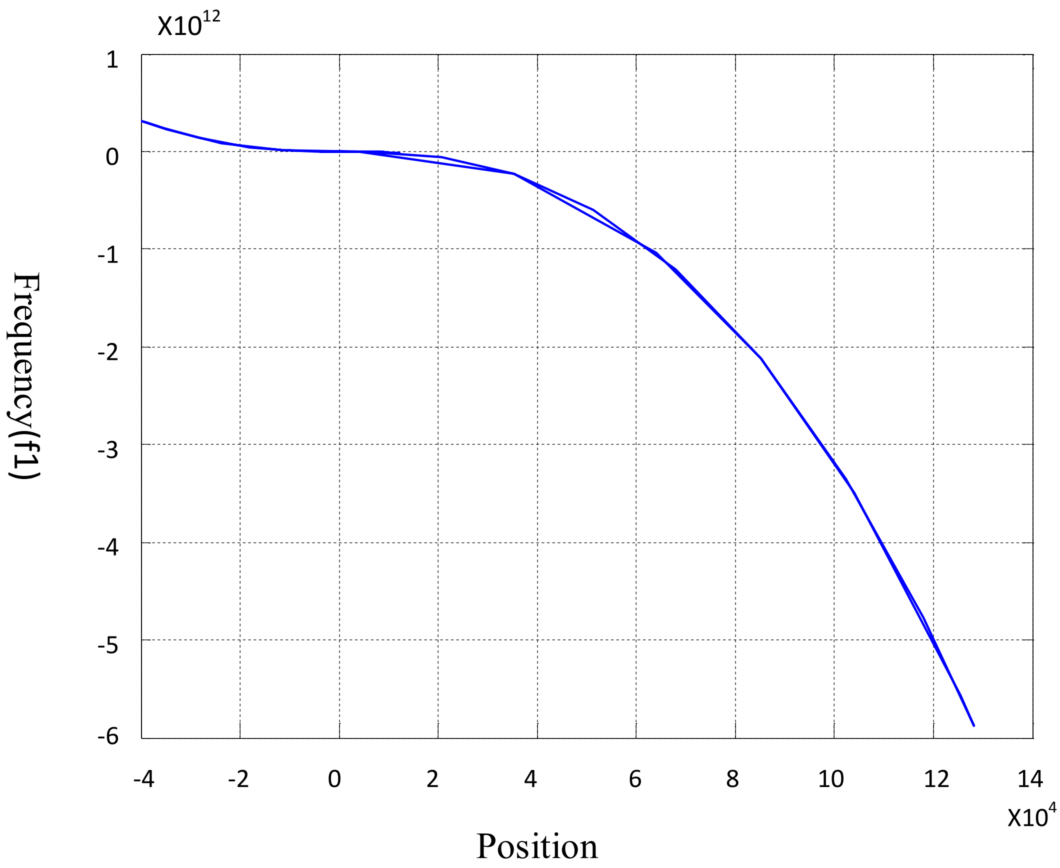

Figure (4.11) spatial position vs. Simulation frequency (f1)

4.5.5 Time vs. Simulation frequency (f)

While running the simulation of the system the cantilever stable at frequency (0)from 0 to 2 (simulation time) but it change by increasing the frequency and also decreasing until stable at frequency equal zero , in this frequency investigated the stability of the cantilever .See figure (4.12)

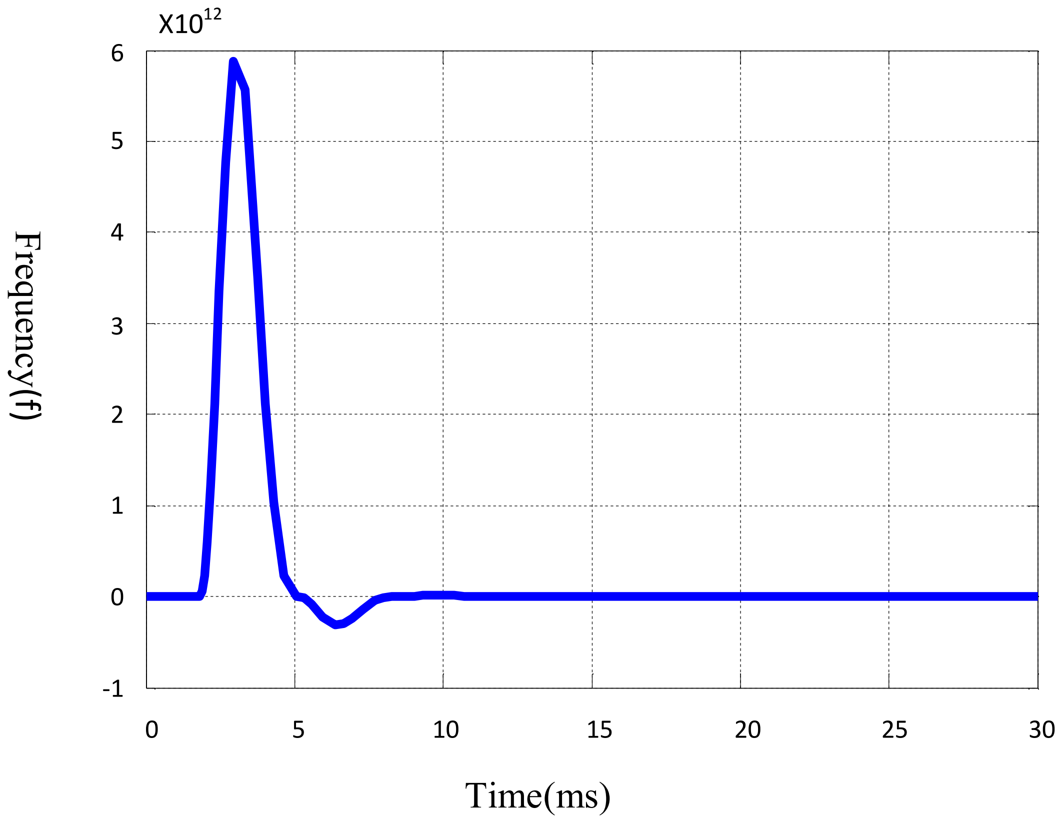

Figure (4.12) Simulation Time vs. frequency (f)

4.5.6 Time vs. Simulation frequency (f1)

While running the simulation of the system the cantilever stable at frequency (0)from 0 to 2 (simulation time) but it change by decreasing the frequency and also increasing until stable at frequency equal zero , in this frequency investigated the stability of the cantilever .See figure (4.13)

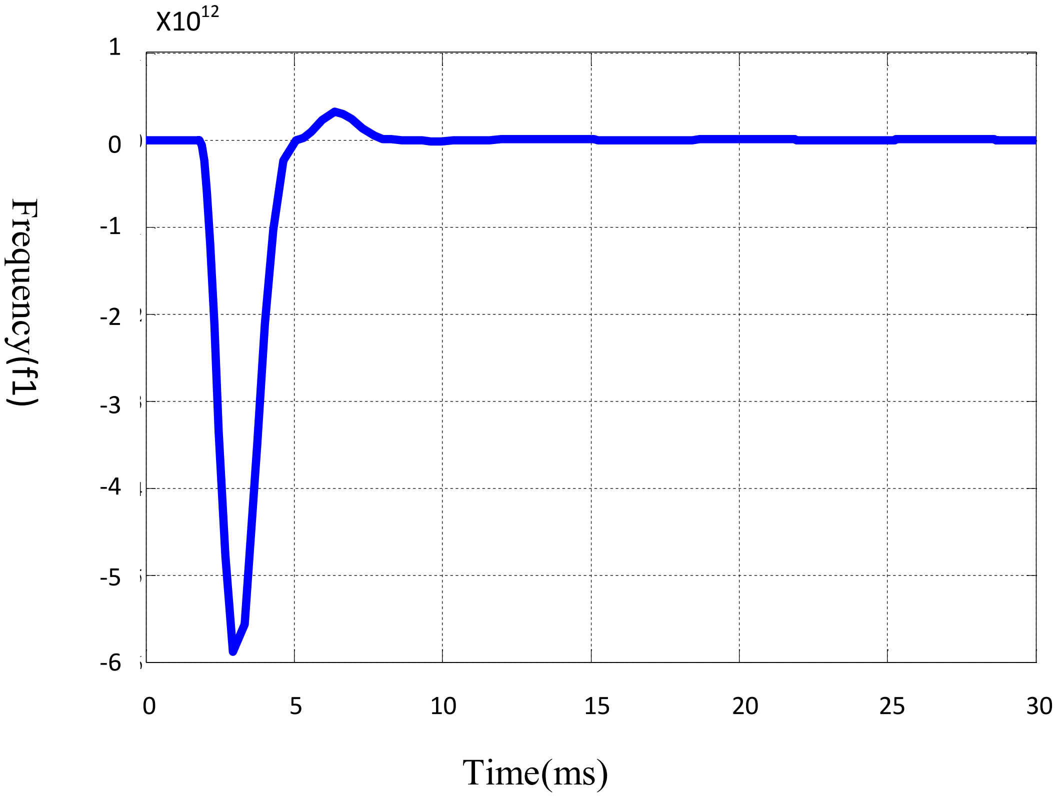

Figure (4.13) Simulation Time vs. frequency (f1)

4.5.7 Time vs. Simulation reference voltage

When the starting of the simulation the reference voltage is 0.35 (constant) in all of the simulation .See figure (4.14)

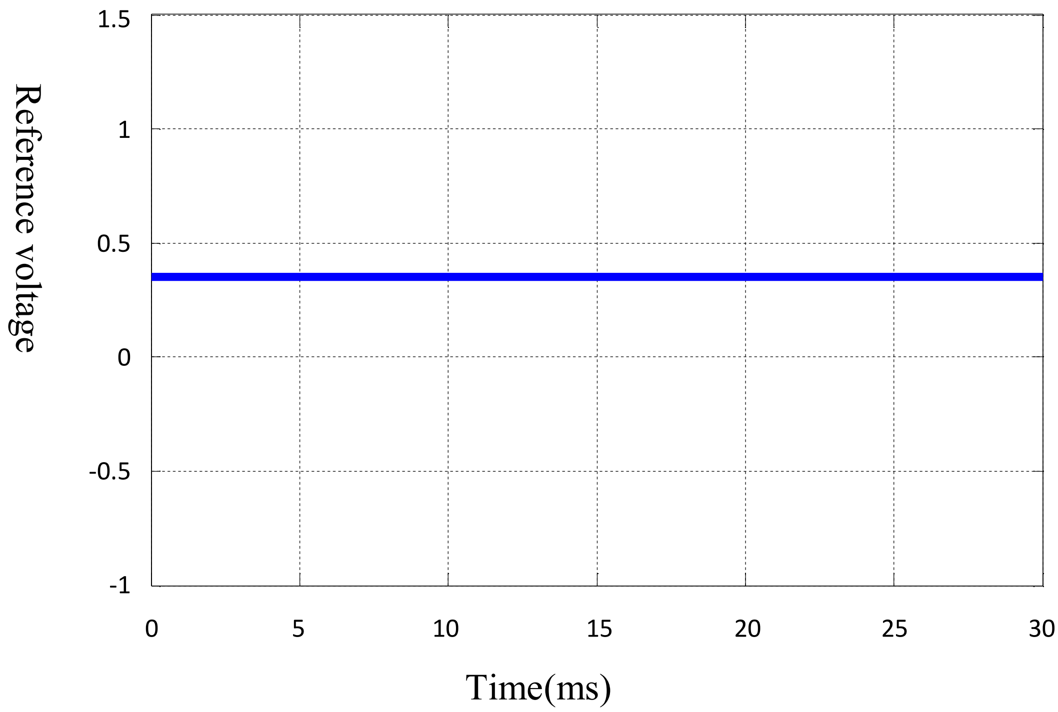

Figure (4.14) Simulation Time vs. reference voltage

4.5.8 Table of Disturbance reading description

NO	Items	Reading
1	Rise time	0.495
2	Peak time	0.435
3	Max overshoot	2.0332e+5
4	Settling time	0.495
5	Actual position	0

Table(4.2) for disturbance reading

Chapter Five

Conclusion and Recommendations

Chapter Five

Conclusion and Recommendations

5.1 Conclusion

The MEMS technology based on a feedback control theory used mainly for stabilization and the control theory can be defined an interdisciplinary branch of engineering and mathematics that deals with the behavior of dynamical systems with inputs, and how their behavior is modified by feedback. The difference between actual and desired output, called the error signal, is applied as feedback to the input of the system, to bring the actual output closer to the reference. The problem behind the project is to the increased weight and volume, increased power consumption, Increase design area and the variation of the supply and movement represented in Non-stability could damage the system before MEMS.

The developed system was tested and it has a stability of MEMS Cantilever Beam using the closed loop control system.

Control system development for these problems has traditionally been based on Taylor-series-linearized system dynamics in conjunction with linear control techniques.

Since the system dynamics will behave differently in different parts of the state space, several controllers will have to be designed and "scheduled" with respect to the operating conditions to yield acceptable control system performance. In many situations, coming up with a satisfactory controller schedule can consume far more human resources than the linearization and linear system design tasks. Moreover, the stability of the resulting system cannot be guaranteed.

Nonlinear control methods take advantage of the given nonlinear system dynamics to generate high-performance designs. No Taylor series linearization or gain scheduling is required for their implementation. These features free the designer to focus on the control system design aspects of the problem, leaving tedious model manipulations to the software.

5.2 Recommendations

1- Using simulation software for accurate results.
2- Compare results with other programs.
3- Evaluate the performance of MEMS in other applications.

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