Neural network controller for parallel plate pull-in instability

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Pull-in instability of the electrostatic parallel plate is essential for good performance. This paper presents closed loop controlling technique for the electrostatic actuated parallel plate to extend the travelling length and to get better pull-in instability performance. Almost full gap length is obtained by using the controlling technique. Pull-in analysis is presented for an electrostatic parallel plate. Parallel plate mathematical model is presented with normalized parameters. Neural network controller has been used. Exact radial bias is designed and trained from practical examples for such parallel plate. The neural network controller produces (1.25-5) % error at different travelling lengths. Desired performance is obtained by controlling the input voltage signal to the parallel plate.

هذا البحث يقدم دراسة وافية لإستقرار الألواح المتوازية فى مرحلة الجذب النهائى. كما يقوم البحث بتقديم نظام تحكم مغلق المسار لمد المسافه المقطوعة بواسطة الوح المتحرك بالنسبة الى الوح الثابت والحصول على أداء أفضل فى حالة الجذب النهائى. تقريبا تم الحصول على معظم المسافة الواقعه بين اللوحين كمسافة مقطوعة بالنسبة للوح المتحرك عند استخدام هذا النظام المقترح للتحكم. كما قام البحث بعرض المعادلات الرياضية المعبره عن النظام كما تم التعبير عن متغيرات النظام بنظام الوحده الموحده. كما تم استخدام نظام الشبكات العصبيه لبناء المتحكم. كما تم اختيارنظام الانحياز الشعاعى فى التحكم و قد تم تدريبها و تصميمها من خلآل بيانات مأخوذة من أمثلة عمليه. نظام التحكم باستعمال الشبكات العصبيه اعطى نسبة مقبولة للخطأ وهى (١,٢٥- ٥)% وذلك عند مسافات مقطوعه مختلفه بواسطة اللوح المتحرك.و قد كما تم الحصول على الأداء المطلوب للألواح المتوازية عند حالة الجذب النهائى بعد إستعمال طريقة التحكم بواسطة الشبكات العصبية.

Keywords: MEMS, Pull-in, Parallel plate, Neural network, Radial bias

1. Introduction

One important difficulty in developing electrostatic actuators for positioning applications is the pull-in instability. That always happens because of the nonlinear electrostatic force. This can be quite problematic for positioning and tuning applications, particularly for optical and RF system applications where large movements and tuning ranges are important. There are some studies to overcome the pull-in instability problem. The recommended travelling length in the gap to avoid the pull-in is 1/3 gap length, where at 2/3 gap length, the pull-in starts. In [1] Seeger and Cary propose a stabilization technique using a matched MOS capacitor in series with an electrostatic actuator.

Parasitic capacitance in parallel with the actuator itself, it can cause problems. If the actuator capacitance increases, charge from these parasitic capacitances will be drawn out, tending to further increase in the actuator capacitance and attractive force. Burns and Bright [2] use multi-phase nonlinear flexure to extend travel distance. The idea is to compensate for the nonlinear nature of the electrostatic force by designing a restoring force that gets stiffer as the actuator gap gets smaller. Burns and Bright implemented a multi-layer piecewise linear flexure that comes into contact with successively stiffer springs as the actuator moves. Since the electrostatic force grows without bound as the gap becomes smaller, higher order springs are necessary for more travel, however, in one experiment. The primary drawback with this approach is complexity of the multiphase flexure.

Leveraged bending actuation technique [3] is presented in order to achieve complete gap vertical travel of an electrostatically actuated mirror without pull-in. The idea is to place actuation electrodes under only a portion of the structure, then use the rest of the structure as a lever to position key parts of the structure through a large range motion. The drawback of this method is that, it can not be

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applicable for all the optical and scan applications.

Another method for avoiding problems from the pull-in effect is to simply operate structures past pull-in. In [4], there is a demonstration how contact “Zipper” actuators can be used to implement tunable capacitance devices for use in RF systems. The idea is to actuate a deformable structure past any pull-in instabilities so that contact occurs with electrode separated by an insulating layer or mechanical spacer. Changing the actuation voltage in this regime deforms the structure, resulting in a change in the contact area, thereby positioning or tuning the structure appropriately. The possible drawbacks to this approach include the application of an offset voltage or separate electrode to actuate past pull-in, and possible stiction and hystersis issues involving contact of moving parts.

Many other techniques to solve the instability problem are presented in the literature [5-6]; they describe similar techniques as shown above. Another method for overcoming the pull-in instability problem is to use active feedback control. The idea is to actively sense the position of the actuator to stabilize position by reducing the voltage if the gap decreases, and increasing the voltage if the gap increases. [7] reports an algorithm for closed loop voltage control of electrostatic actuators.

Active control is promising; however, there are a number of practical implementation issues. First, sensing position and feeding back the information can be difficult and expensive to implement. Capacitive position sensing and control often requires integrated electronics. The control problem is also nonlinear. The $1/Z^2$ (where Z is the movable plate displacement) dependence on electrostatic force means it becomes more difficult to stabilize the actuator as the gap decreases. In addition, designing the controller generally requires simulation the dynamics of the system, which might be complicated, for example if squeeze film damping due to air must be included.

2. Parallel plate characteristics

The basic configuration of the parallel plate is just two conductive plates such that, we can develop some fundamental relationships for force, displacement and energy that will be useful for our discussion and analysis of that actuator.

Assume the lower plate is fixed in place to ground and that the upper plate is connected to constant potential V. The two plates each has area A, and are separated by distance X. called the gap. A force F holds the upper plate in the equilibrium position shown. By neglecting the fringing field and the separating material between the two plates has a dielectric constant ε_o (where ε_o is the permittivity of the free space $8.85*10^{-12}$). The stored potential energy in the electric field is given by eq. (1).

$$E_{field} = \frac{1}{2}CV^2 . \quad (1)$$

Where E_{field} is the stored potential energy between the plates, V is the applied voltage on the parallel plates and C is the plate capacitance, the plate capacitance changes with the change of the gap between the two plates. The parallel plate capacitance is shown in eq. (2). The parallel plate capacitance has inverse proportionality with gap length X. The applied electrostatic force (F_{field}) on one plate versus the plate displacement X is shown in eq. (3).

$$C = \frac{\varepsilon A}{X} . \quad (2)$$

$$F_{elect} = \frac{1}{2} * \frac{\varepsilon A}{X^2} * V^2 . \quad (3)$$

The eqs. (1), (2), (3) have been simulated and the results are shown in fig. 1, fig. 2 by dividing eq. (3) by the plates area we can find the pressure on this plate as shown in fig. 2. From these figures one can conclude that, the capacitance decreases as the displacement increases. Which means that, the moving mass goes up in our plan; meanwhile the energy stored in the electrostatic field decreases and the electrostatic filed strength decreases as well. As the displacement decreases, the moving mass goes down and energy stored on the electrostatic field increases also the speed of the moving mass increases very rapidly due to the large increase in the force because of the large increase in the electrostatic field and the

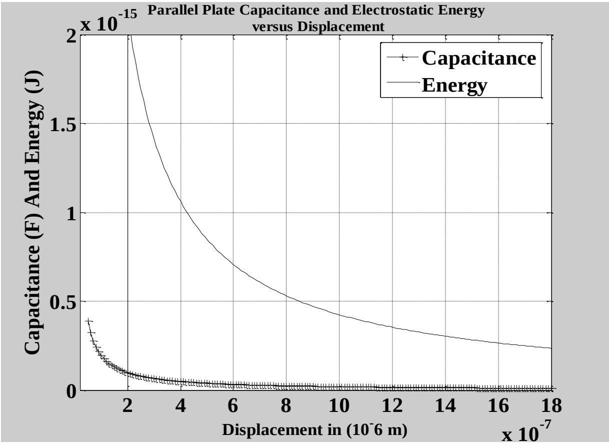

Fig. 1. Parallel plate capacitance and energy versus the plate displacement for DC input voltage.

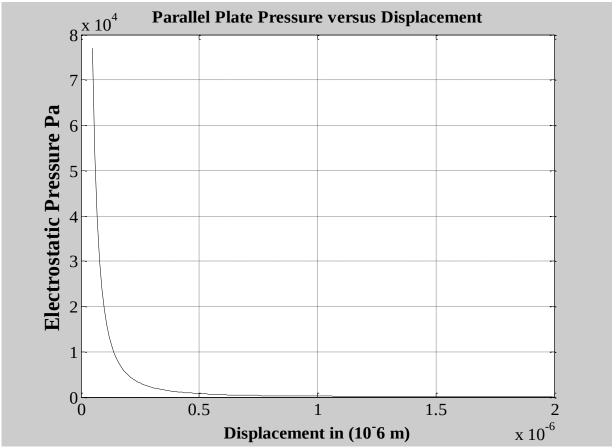

Fig. 2. Parallel plate electrostatic pressure versus the plate displacement for DC input voltage.

two plates stick together which describes the pull-in instability and the failure of the device. To solve the problem, active control will be developed using neural network radial bias in the coming sections.

3. Analysis and mathematical model for dc input voltage

Before developing the neural network controller, the system model should be developed first as follows. The parallel plate can be modeled as shown in fig. 3, by a mass (*m*), damper (damping coefficient *b*) and spring (stiffness coefficient *k*). The mathematical model for the parallel plate system is divided to two main equations. First, the mechanical equation,

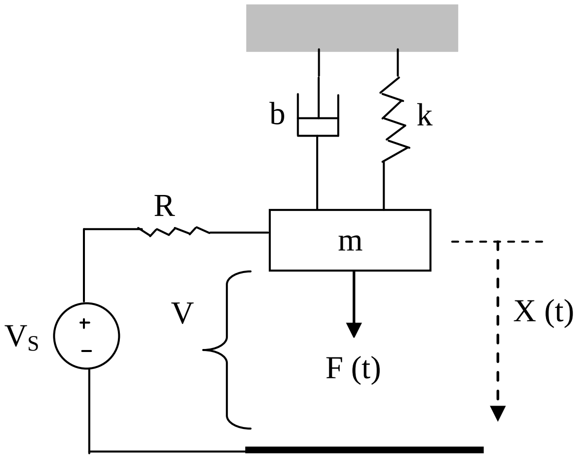

Fig. 3. Parallel plate model.

which can be developed using Newton equation for motion as, follows in eq. (4).

$$m\frac{d^2X}{dT^2} + b\frac{dX}{dT} + kX = F_{elect} \,. \tag{4}$$

Where T is the time, X is the plate displacement, from eq. (3), the electrostatic applied force can be represented as in eq. (5).

$$F_{elec} = \frac{Q^2}{2C_oG_o} = \frac{\varepsilon_o A V^2}{2X^2} \,. \tag{5}$$

Where G_o is the initial gap length, C_o is the plate capacitance at zero displacement, Q is the charge accumulated at the plate surface. The other equation in the mathematical model is the electrical equation, which can be developed from the loop equation as follows.

$$V_S = iR + V \,. \tag{6}$$

Where R is the source resistance, i is the loop current, V_S is the source voltage. By replacing the current i with the charge rate $\frac{dQ}{dT}$ we can get eq. (7).

$$\frac{V_S}{R} = \frac{V}{R} + \frac{dQ}{dT} \,. \tag{7}$$

In order to implement the neural network controller, it is useful to normalize these equations as follows. Distance is normalized to the initial gap length G_o, time is normalized to the inverse of the undamped mechanical resonance frequency ω_o, voltage is normalized to the pull-in voltage V_{PI}, and charge is normalized to the pull-in charge Q_P which is the charge stored when the capacitor voltage is equal to V_{PI} and gap is reduced to 2/3 the initial gap length, the new normalized variables are:

$$x = \frac{X}{G_o} \quad t = \omega_o T \quad q = \frac{Q}{Q_P}$$
$$\upsilon_S = \frac{V_S}{V_{PI}} \text{ where}$$
$$C_o = \frac{\varepsilon A}{G_o} \quad V_{PI} = \sqrt{\frac{8kG_o^2}{27C_o}}$$
$$Q_P = \frac{3}{2}C_o V_{PI} \quad \omega_o = \sqrt{\frac{k}{m}} . \tag{8}$$

The system-normalized equation can be derived using eqs. (4), (5), (7), (8) and represented as shown in eqs. (9), (10)

$$\ddot{x} + \frac{b}{2m\omega_o}\dot{x} + x = \frac{q^2}{3} , \tag{9}$$

$$\frac{dq}{dt} + \frac{q}{R\omega_o C_o}(1-x) = \frac{2\upsilon_S}{3R\omega_o C_o} . \tag{10}$$

As shown from the normalized system model eqs. (9), (10), the system is nonlinear so, to build controller for such system we should linearize the system. But, that will not give accurate results, but here neural network can deal with such systems, so, here the neural network controller can overcome this problem and gives more accurate results.

4. System results and simulation for DC input voltage

Extensive transient simulations for various values of the parallel plate parameters have been performed using MATLAB. These parameters values were selected based on practical examples found in the literature [8]. The transient response of the system is shown in fig. 4. The normalized charge grows up with time. The mass starts its motion at 0.005 of the normalized time due to the low inertia. We can classify the parallel plate response into three main phases. The first is the acceleration phase, which lasts until a normalized time of about 2. During this phase, the parallel plate charge increases rapidly, and the velocity increases slowly but the position is still close to the initial position. The second phase is damping phase where all the three parameters are still increasing but at lower rate because of the nonlinear electrostatic force. The final phase is the pull-in phase which characterized by a rapid increase in the velocity with the mass moving towards the final position (x=1).

5. System model and simulation for AC input voltage

For AC voltage input the pull-in instability does not make big problem like in the case of DC voltage input. The mechanical equation will be the same as in eq. (4), the difference here in this case is the electrical equation. The parallel plate can be represented as variable capacitive reactance. This capacitive reactance depends on the gap length between the two plates. Eq. (11) represents electrical model for variable capacitive reactance.

$$V_S = iR - JiX_C . \tag{11}$$

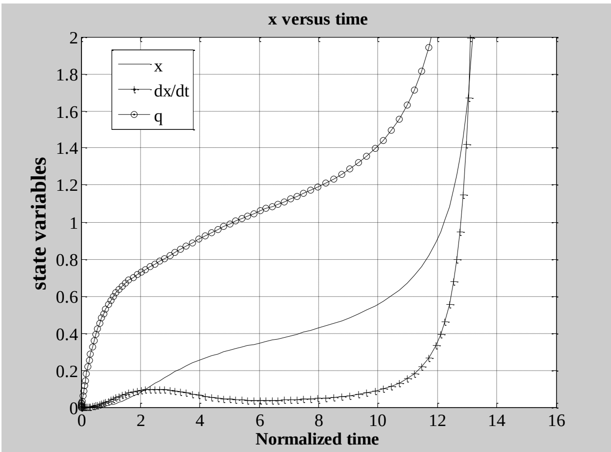

Fig. 4. Normalized displacement, velocity and charge versus normalized time for DC input voltage.

This variable capacitive reactance can be represented as in eq. (12). By the same steps as in above, we can get the electrical mathematical model for the parallel plate with AC input voltage as in eq. (13).

$$X_C = \frac{1}{\omega C} = \frac{1}{\frac{\omega \varepsilon A}{G_o - X}} , \tag{12}$$

$$\frac{dQ}{dT} = \frac{V_S}{R - J\frac{(G_o - X)}{\omega \varepsilon A}} . \tag{13}$$

The normalization for this equation can be found by using eqs. (8), (13). Eq. (14) represents the normalized electrical equation.

$$\frac{dq}{dt} = \frac{\upsilon_S}{\frac{3}{2}C_o\omega_o R - J\frac{3(1-x)}{2\omega}} . \tag{14}$$

So, eqs. (9), (14) represent the normalized parallel plate mathematical model for AC input voltage, these equations have been simulated using MATLAB for different input frequencies.

Fig. 5 shows the system response for AC input voltage signal with very small frequency close to zero 0.402 rad/sec. As shown the charge has sine wave increasing and decreasing, goes positive and negative following the source voltage. The moving plate speed has also sine wave moves in two opposite directions according to the applied force. The displacement of the moving plate has some ripples according to the applied force. This figure explains that, the pull-in instability can not happen in the case of AC input voltage, where the moving plates changes its direction according to the sin wave electrostatic force. So, the pull-in instability does not have effect in this case.

For more description and investigations, the simulation has been run for input signal has the natural system frequency ω_o = 402 rad/sec. Fig. 6 shows the moving plate displacement and speed. The moving plate has just overshoot and stays on constant displacement from the fixed plate. The speed has small sine wave and stays at zero (i.e. static plate). That means, the moving plate could not follow the system input signal frequency. Fig. 7 shows the charge accumulated on the plate, it almost follows the input signal frequency and magnitude variations. But the charge accumulated is only positive which makes the moving plate displacement. i.e. the system is on equilibrium state.

Fig. 8 shows the moving plate displacement and speed for very high input frequency at 10*ω_o. The moving plate has overshoot and stays on lower displacement from the fixed plate than natural frequency input frequency (ω_o). The speed stays at zero in the steady state part. That means, the moving plate could not follow the system input signal frequency.

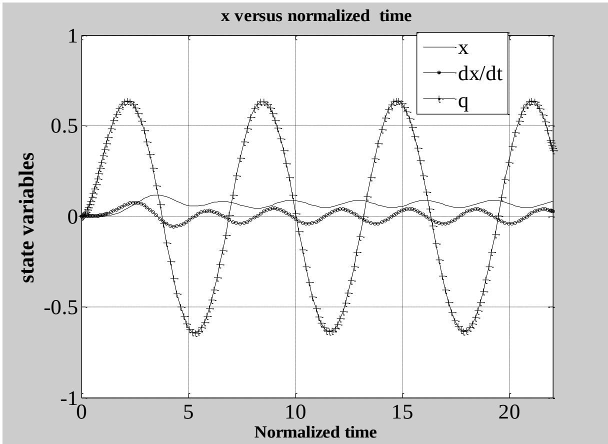

Fig. 5. Normalized displacement, velocity and charge versus normalized time for AC voltage input with 0.402 rad/sec.

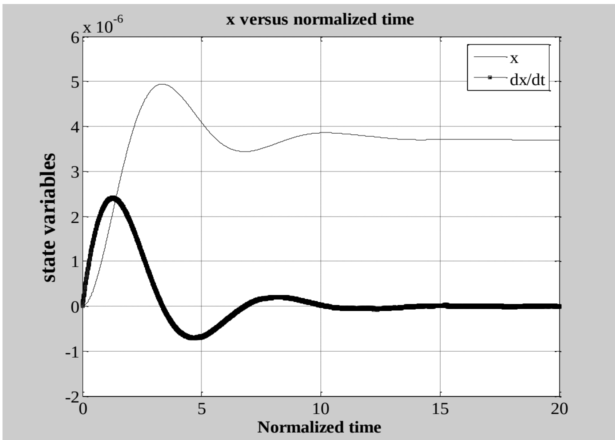

Fig. 6. Normalized displacement and velocity versus normalized time for AC voltage input with 402 rad/sec.

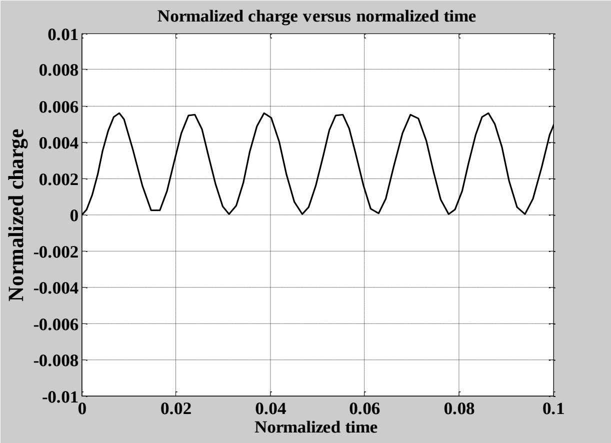

Fig. 7. Normalized charge versus normalized time for AC voltage input with 402 rad/sec.

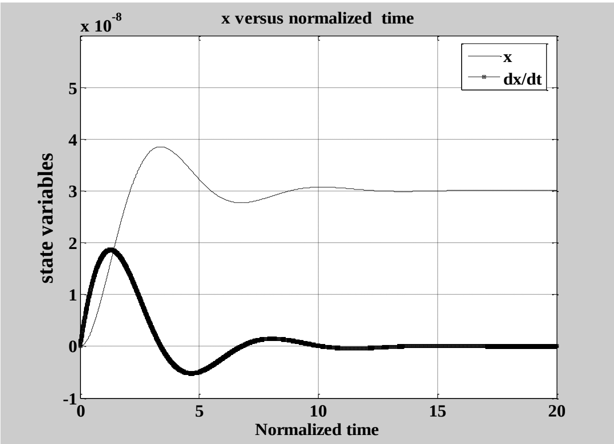

Fig. 8. Normalized displacement and velocity versus normalized time for AC voltage input with 4020 rad/sec.

Fig. 9 shows the charge accumulated on the plate, it almost has the input signal frequency. But the charge accumulated is positive, which makes the moving plate displacement. i.e. the system is on equilibrium state.

6. Controller design

The idea of the controller here is to control the charge accumulated on the plates by increasing or decreasing the applied voltage on the actuator. Controlling the voltage comes from the feedback system (controller gain). The proposed control system connection is shown in fig. 10, the closed loop system input is the normalized source voltage (υ_S), the closed loop system output is the plate normalized displacement (x), the feedback gain is the neural network controller, where the neural controller input is the normalized displacement and its output is the normalized voltage signal to be subtracted from the normalized source voltage. The parallel plate system is represented by a system of nonlinear differential equations as shown above in eqs. (9), (10), where the neural network is the best choice for controlling such nonlinear system without linearization for better simulation accuracy.

7. Neural network controller design and training

The exact radial bias technique is chosen and implemented using MATLAB neural network toolbox, the network could be designated in different ways, many assumptions exits in

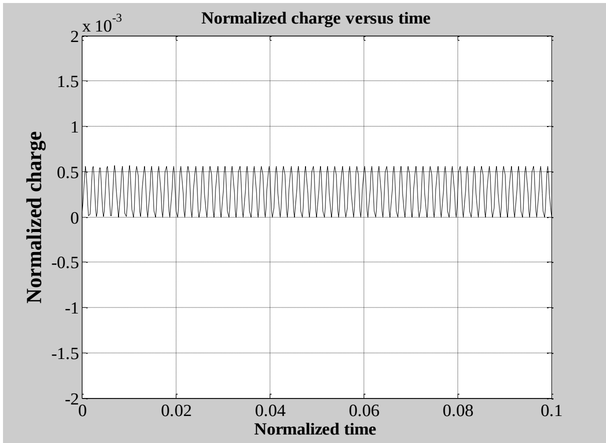

Fig. 9. Normalized charge versus normalized time for AC voltage input with 4020 rad/sec.

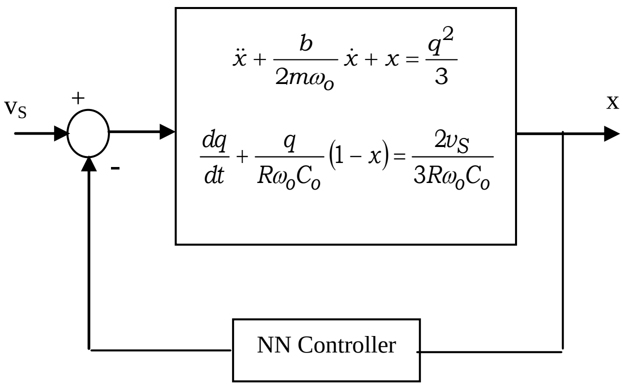

Fig. 10. Block diagram for closed loop system.

the literature [9,10] for the number of hidden layers, number of neurons in each layer, type of activation function for each layer. Fig. 11 shows schematic diagram for the radial bias neural network controller for single input, single output system. The training input vectors and target vectors of the radial bias network have been found from many simulation results for the parallel plate model. Fig. 12 shows one of these training vectors that for normalized displacement, speed and charge versus the normalized time. The network has been designed with input bias at each neuron; the gain and the system stability have been checked and designed during the training process.

8. System results and simulation after using the control system

The idea of the controller work is described as. The input voltage controls the charge on the plates, where as the charge increases and voltage to decrease the charge on the plate. So, as shown from the training vectors shown the moving plate moves down towards the fixed plate, the controller decreases the input in fig. 12, the charge can only increases to a specified limit to guarantee that, the moving plate will not stick with the fixed one. The figure also shows the plate speed, which depends on the applied electrostatic force according to the applied voltage. The plate speed grows up gradually with low rate to insure good pull-in stability. Also, the applied electrostatic force controls the plate position; we can keep the moving plate on the distance we want away from the fixed plate by controlling the input voltage to the actuator.

A simulation has been done using MATLAB for the closed loop system in fig. 10. The same parameters values as in above used in this part to make the comparison between the two different situations (with control and without control) easy. Fig. 13 shows the system response (normalized displacement and speed) of the closed loop system for 0.2 travelling length in the gap. Fig. 14 shows the normalized charge versus the normalized time. As shown, the charge increases in the transient part and then reaches to the specified normalized value, which produce the predetermined plate position. Also at that position the speed goes to zero to keep the plate static at the predetermined position.

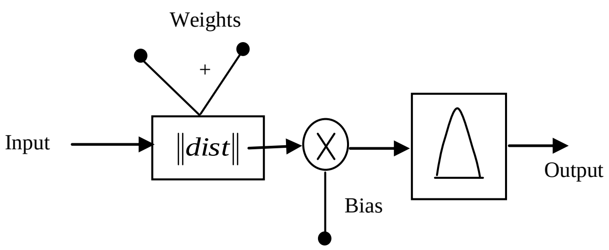

Fig. 11. Radial bias schematic diagram.

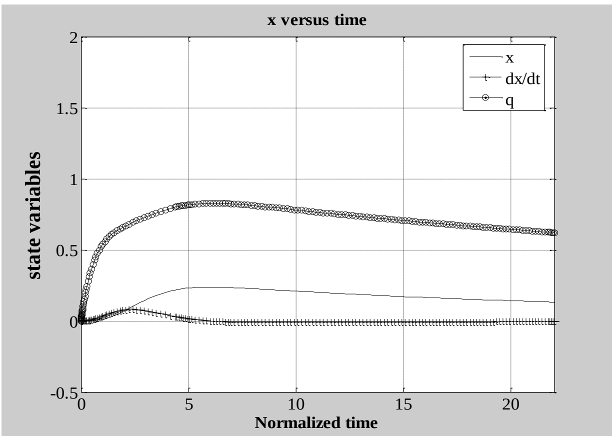

Fig. 12. Training vectors for radial bias neural network for normalized displacement, velocity and charge versus normalized time after using the neural network controller for 0.2 travelling length for DC input voltage.

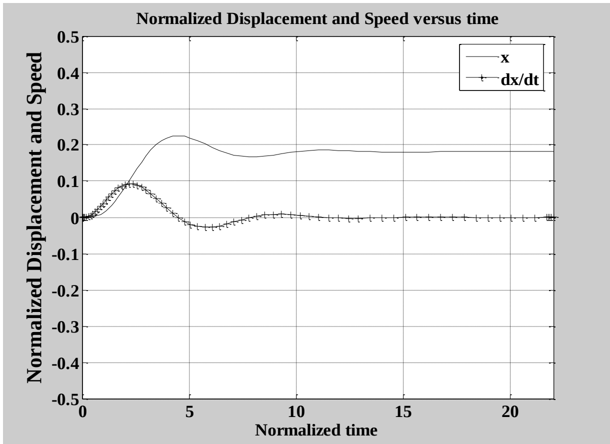

Fig. 13. Normalized displacement, velocity and charge versus normalized time after using the neural network controller for 0.2 travelling length for DC input voltage.

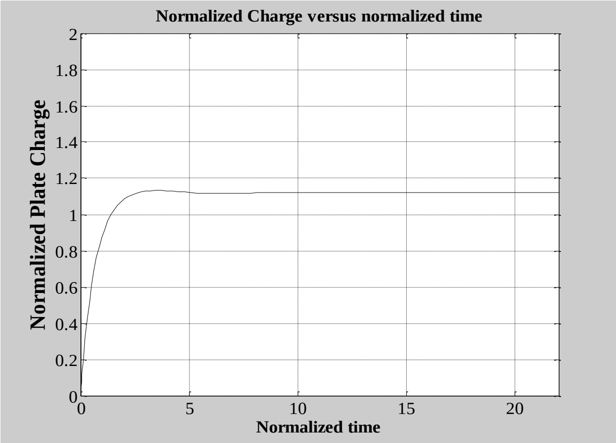

Fig. 14. Normalized charge versus normalized time after using the neural network controller for 0.2 travelling length for DC input voltage.

The system response can be divided to two main phases transient and steady state parts. In the transient part the voltage inputs to the plate increases gradually, and then the accumulated charge, and the controller each time measure the moving plate position to determine the feedback voltage. The plate speed increases and decreases according to the system inertia and the accumulated charge on the plate. There is over shoot on the plate position that causes the speed to change its direction in the transient part.

The moving plate final position is at 0.19 per unit travelling length, which makes controller error of 5%. Fig. 15, fig. 16 show the same parameters described above for controlling position at 0.8 per unit travelling length, that could be done by retraining the controller for the new position by curves like that shown in fig. 12. The moving plate final position is at 0.79 per unit travelling length, which makes controller error of 1.25 %.

9. Conclusions

Parallel plate analysis and mathematical model have been presented with controlling objective in mind. Parallel plate model is presented and simulated using MATLAB. Pull-in instability for such actuators has been presented and investigated. The problem is explained for dc and ac voltages. The study presented that, the only allowable travelling

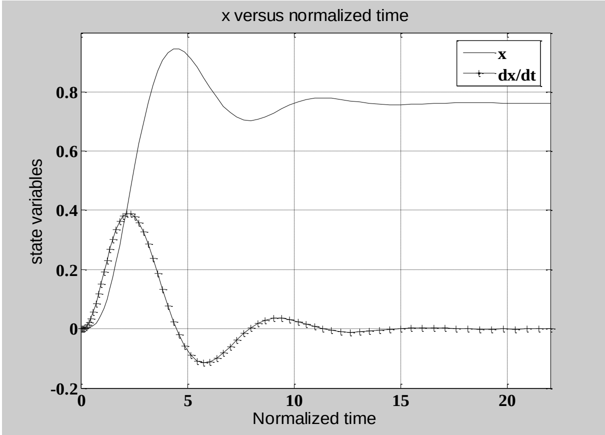

Fig. 15. Normalized displacement and velocity versus normalized time after using the neural network controller for 0.8 travelling length for DC input voltage.

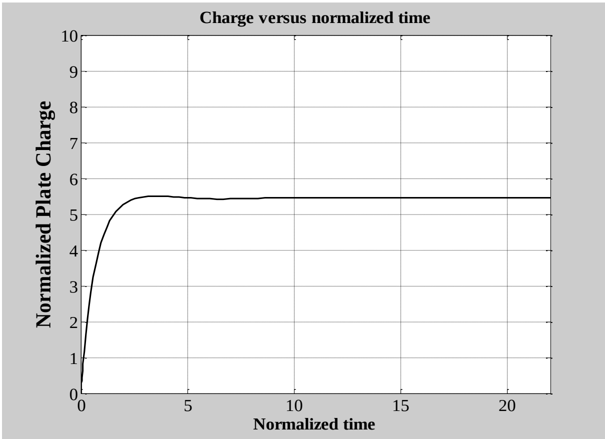

Fig. 16. Normalized charge versus normalized time after using the neural network controller for 0.8 travelling length for DC input voltage.

length in the gap can not increases more that 1/3 gap length, where the system enters the pull-in state at 2/3 gap length. Neural network controller has been built and designed for such purpose. Exact radial bias neural network has been chosen and trained for different travelling length. The training vectors for the neural network controller have been found from different simulations for the same system and parameters values. Closed loop system is presented. The controller error ranges between (1.25-5) %. Using the controller increases the travelling length to almost full gap.

Reference

[1] J.I. Seeger and Victor D. Samper, "Stabilization of Electrostatically Actuated Mechanical Devices", Transducers, pp. 1133-1136 (1997).
[2] D. M. Burns and V. M. Bright, "Nonlinear Flexures for Stable Deflection of an Electrostatically Actuated Micromirror", Proc. SPIE, Microelectronics Structures and MEMS for Optical Processing III, Vol. 3226, pp. 125-135 (1997).
[3] E.S. Hung and S.D. Senturia, "Leveraged Bending For Full-Gap Positioning with Electrostatic Actuation", Proc. Solid State Sensor and Actuator Workshop, Hilton Head, SC, pp. 98-100 (1998).
[4] E.S. Hung and S.D. Senturia, "Tunable Capacitors with Programmable Capacitance Voltage Characteristic", Proc. Solid State Sensor and Actuator Workshop, Hilton Head, SC, pp. 292-295 (1998).
[5] S.E. Hung and Stephen D. Senturia, "Extending the Travel Range of Analog-Tuned Electrostatic Actuators", IEEE Journal of Microelectromechanical Systems, Vol. 8 (4), pp. 497-505 (1999).
[6] Rob Legtenberg, John Gillbert, D.S. Stephen and Miko Elwenspoek, "Electrostatic Curved Electrode Actuators", IEEE Journal of Microelectromechanical Systems, Vol. 6 (3), pp. 257-265 (1997).
[7] P.B. Chu and K.S. Pister, "Analysis of Closed Loop Control of Parallel Plate Electrostatic Microgrippers", Proc. IEEE Int. Conf. Robotics and Automation, pp. 820-825 (1994).
[8] Luis M. Castaner and D.S. Stephen, "Speed-Energy Optimization of Electrostatic Actuators Based on Pull-in", IEEE Journal of Microelectromechanical Systems, Vol. 8 (3), pp. 290-298 (1999).
[9] L.F. Terrence, "Feed Forward Neural Network Methodology", Springer-Verlag New York, Inc., ISBN 0-387-98745-2 (1999).
[10] Martin Anthony and Peter L. Bartlett, "Neural Network Learning: Theoretical Foundations", Printed in UK, Cambridge University, ISBN 0 52157353 X Hardback (1999).

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