Journal of Artificial Intelligence in Electrical Engineering, Vol. 7, No. 28, March 2019

Analysis of Motion of Micro-Gripper Exposed to the Electric Field and Thermal Stresses for Using in Micro-Robotics

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Abstract

Micro system technology is a relatively new scientific research that deals with the development and study of properties of materials in micro dimensions. Micro-grippers are widely used in switching, positioning, and assembling micron sized components in micro-robotics. In this study, the static and dynamic behavior of visco-elastic Micro-Tweezers under the thermal and electrostatic field is studied numerically. In order to consider more realistic assumptions, the visco-elastic behavior is investigated and thermal effects are simulated by considering both linear and nonlinear models. Considering Euler-Bernoulli beam theory, governing differential equation of motion are derived. Finally, the effect of different parameters such as the parameter of visco-elastic parameters, the effects of temperature and intensity of the electrostatic field on the dynamic and static characteristics of the Micro-Tweezers have been investigated. The results show that visco-elastic behavior has a significant effect on the dynamic behavior of Micro-Tweezers, and with its increase, the damping of the system increases and the amplitude of the Micro-Tweezers oscillations decreases. The system's damping increases from 0.01 to 0.08, the maximum amplitude of Micro-Tweezers decreases from 0.9 to 0.66.

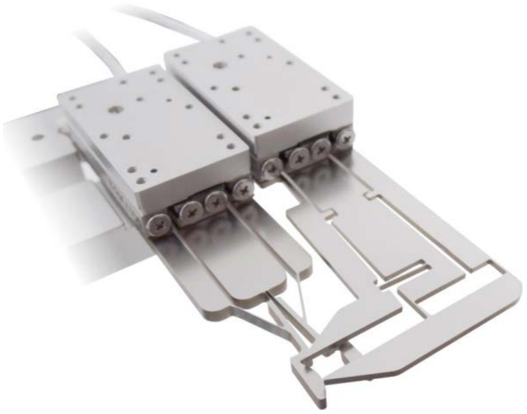
Keywords: Micro-robot; Micro-gripper; Instability; Dynamic Analysis; Thermal Stress

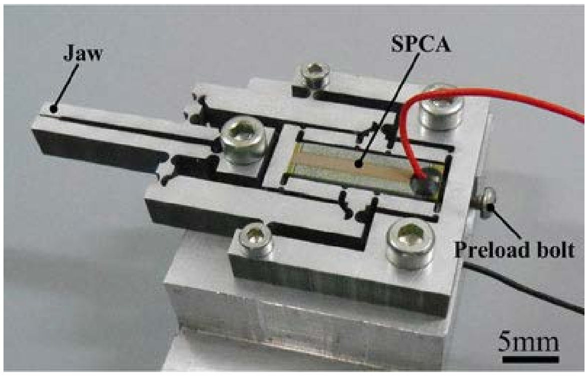
1- Introduction

In 1951, Richard Finnman, a physicist who later received the Nobel Prize, established a theory that can be called the first human movement towards micro and nano-technology. In his theory, he stated that the rules of physics do not have any constraints in moving and transporting the structure of air atom and air molecule. In his speech, he discussed about transportation, movement, and controlling in small scales. He predicted that a new generation of micro-equipments is required to work with and control tiny particles in a smart way. Since then, as the technology and the design of systems are developing, micro-robots have been utilized as human equivalents in micro-levels to apply external orders to do appropriate tasks on certain systems such those in limited surgeries within the human body. In micro-robots, the part that carries out the proper works of transporting the particles is known as micro-grippers.

As the use of tools with micro and nano scales is increasing in different fields, using micro-grippers as tools to take and transport things has become widespread. Some of these functions are in biology, micro-robots, and surgery equipments. Different mechanisms such as electric force, piezoelectric, pneumatic, and electro-thermal are utilized to move the arms of micro-grippers.

Micro-gripper is a tool to hold objects in micrometer sizes and moving them. In fact, they create a bridge between humans and the world which is only observable under a microscope. In figure 1, different samples of micro-grippers have been represented. In this way, we can manipulate objects with only several micrometers or even some nono-meters and such a capability is highly valuable in micron transportations. The micro-gripper is expected to approach the intended object easily and transport and release the object after removal of it in a healthy mode onto the predetermined location.





In some cases it is necessary to use micro-grippers in warm areas or to use them in order to carry particles with high temperatures and in this state we should notice the visco-elastic materials' behavior in simulations. The investigations carried out before showed that although the mechanical behaviors of micro-grippers made of a congruent material have been probed till now, the mechanical behavior and the consistency of micro-grippers have not been investigated presupposing the visco-elastic behaviors. Therefore, in the present research and to consider more real presuppositions, the effects of visco-elastic behaviors in the structure of micro-grippers have been taken into consideration and the static, dynamic, and consistency of micro-grippers have been investigated in the presence of external stimulants. Through modeling micro-grippers formed of two micro-grips of dripped in one end, the movement equations have been extracted and after resolving them through appropriate numerical resolution methods, the response and system consistency regarding different voltages will be studied. Finally, the effect of different physical parameters, geometrical dimensions, electro static fields and visco-elastic coefficients on mechanical behavior and system consistency will be investigated.

The use of micro-grippers as a tool to take and move has been developed due to the exceeding progress of using particles in micro-scales and nano-scales in different fields and some examples include their usage in biology, micro-robots, and surgery tools. Different mechanisms such as electro-static [1-2], piezoelectric [3-4], pneumatic [5], magnetic [6], mechanics, and electro thermal have been utilized to move micro-grippers' arms. Electrostatic force is used in structures such as micro-pumps, switches, micro-mirrors, micro-resonators, micro-stimulators, and adjustable capacitors. It is also known as one of the most important stimulator mechanisms in micro-grippers through the enforcement of voltages onto micro-grippers' arms and as the voltage exceeds, its amount is exceeded and this causes more movements of the arms towards each other. As the voltage reaches a critical amount which is the same as system inconsistency voltage, the retrieval elastic force can not neutralize the electrostatic force and inconsistency occurs. Several papers have been published regarding the micro-grippers working with electrostatic stimulators and an article presented by Kim and et. al. [7] is one of them, which deals with designing poly-silicon micro-grippers. Biganzoli and et al. [8], proposed a paper regarding the transportation of particles of micro dimensions. The paper by Millet and et al. [9] is about studying micro-grippers with reinforcement mechanisms. Wierzbicki and et al. [10] carried out a research on micro-grippers utilized in blood vessels. And Chen and et al. [11] investigated about designing a type of hybrid micro-grippers.

Zubir and et al. [12] used experimental tests to investigate about the performance of electro-thermo-mechanical micro-grippers. Their results showed that this piece of instrument is able to carry small pieces with an appropriate pressure amount. The pit of this instrument can carry about 32 micrometers using a very trivial force consumption of about 115 micro watts and it could move pieces between 8 to 40 micrometers somewhat easily. Regarding the fact that the temperature in pit of the operator in this system is highly important, the designed micro-gripper should be cooled down to reach the appropriate and desired temperature. Without considering them, some micro-cooler fans of carbonic nano-tubes are connected to the arms to be able to cool down the temperature on the tip of the arms appropriately. The results of modeling showed that the temperature degree of the tip of the micro-grippers would decrease from 194 to 52 degrees if carbonic nano-tubes are utilized.

2- The equations regarding the movement of micro-grippers

The equation dominating the dynamic movement of visco-elastic micro-grippers could be calculated as follows [13]:

$$\rho A\frac{\partial^2 w}{\partial t^2}+F_{ext}=-EI\frac{\partial^4 w}{\partial x^4}-I\eta\frac{\partial^5 w}{\partial x^4\partial t}+P_t\frac{\partial^2 w_I}{\partial x^2} \qquad (1)$$

Where, F_{ext} represents the force in length for the external loads enforced on micro-grippers including the forces resulted from the electrostatic field. And P_t shows the force resulted from the thermal stress that could be calculated through the following equation [14]:

$$P_t = -\left[\lambda_1 \alpha_t \Delta T + \lambda_2 (\alpha_t \Delta T)^2\right] \qquad (2)$$

The parameter α_t is the length of stress coefficient of the material, and λ_1 and λ_2 are coefficients that could be calculated regarding the fixed amounts of Murnaghan [14].

The electrostatic absorption force is calculated in the form of external expanded load in the length as f_{elect} [15, 16]:

$$f_{\text{elec}} = \frac{1}{2} V^2 \frac{dC}{dg} \qquad (3)$$

Where, V is the difference of the voltage enforced between the microbar and base plate, C is the capacitor capacity of the length unit of the capacitor comprised of microbar and electrode, and g represents the distance between microbar and the electrode expressed as follows:

$$g(x) = g_0 - w(x) \qquad (4)$$

Where, g_0 is the primary distance between microbar and the electrode. Through correction of the edge effects for the thin bar, the capacitor capacity C is calculated using the equation posed by Meijis-Fokkema as follows [17]:

$$C(g) = \varepsilon_0 \left(\frac{b}{g} + 0.77 + 1.06 \left(\frac{b}{g} \right)^{0.25} + 1.06 \left(\frac{b}{g} \right)^{0.5} \right) \qquad (5)$$

Where, $(\varepsilon_0 = 8.854 \times 10^{-12}\,\mathrm{C^2 N^{-1} m^{-2}})$ is the fixed amount of gap pass. Through the application of equations (4) and (5) in equation (2) and after mathematical simplifications, the electrostatic force applied on microbar could be calculated as follows:

$$f_{\text{elec}} = -\frac{1}{2} \frac{\varepsilon_0 b V^2}{(g_0 - w)^2} \times \left[1 + 0.265 \left(\frac{b}{h} \right)^{-0.75} \left(\frac{g_0 - w}{h} \right)^{0.75} + 0.53 \left(\frac{b}{h} \right)^{-1} \left(\frac{g_0 - w}{h} \right)^{0.5} \right] \qquad (6)$$

Regarding the fact that in micro-grippers both bars (electrodes) are moving, the distance between them results from the movement of each of the bars and there would be $g - w_I - w_{II}$. Where, w_I and w_{II} respectively represent the motion function of electrodes I and II in micro-grippers. In such a condition, the equation dominating the dynamic behavior of each of the electrodes would be as follows:

$$\begin{aligned} & I\eta \frac{\partial^5 w_I}{\partial x^4 \partial t} + EI \frac{\partial^4 w_I}{\partial x^4} \\ & - P_t \frac{\partial^2 w_I}{\partial x^2} + \rho A \frac{\partial^2 w_I}{\partial t^2} \\ & \qquad = \frac{1}{2} \frac{\varepsilon_0 b V^2}{(g_0 - w_I - w_{II})^2} \times \\ & \qquad \left[\begin{array}{l} 1 + 0.265 \left(\frac{b}{h} \right)^{-0.75} \left(\frac{g_0 - w_I}{h} \right)^{0.75} \\ + \ 0.53 \left(\frac{b}{h} \right)^{-1} \left(\frac{g_0 - w_I}{h} \right)^{0.5} \end{array} \right] \end{aligned} \qquad (7)$$

$$\begin{aligned} & I\eta \frac{\partial^5 w_{II}}{\partial x^4 \partial t} + EI \frac{\partial^4 w_{II}}{\partial x^4} \\ & - P_t \frac{\partial^2 w_{II}}{\partial x^2} + \rho A \frac{\partial^2 w_{II}}{\partial t^2} \\ & \qquad = \frac{1}{2} \frac{\varepsilon_0 b V^2}{(g_0 - w_I - w_{II})^2} \times \\ & \qquad \left[\begin{array}{l} 1 + 0.265 \left(\frac{b}{h} \right)^{-0.75} \left(\frac{g_0 - w_{II}}{h} \right)^{0.75} \\ + \ 0.53 \left(\frac{b}{h} \right)^{-1} \left(\frac{g_0 - w_{II}}{h} \right)^{0.5} \end{array} \right] \end{aligned} \qquad (8)$$

Through the identification of dimensionless variables in the form below:

$$\xi=\frac{x}{L},\quad \eta=\frac{W}{g_0},\quad \beta=\frac{b}{h},\quad S=12\frac{\varepsilon_0 bL^4}{EIg_0^3},$$
$$\Pi=\frac{PAl^2}{EI},\quad \tau=\frac{t}{l^2}\sqrt{\frac{EI}{\rho A}},\ \mu=\frac{1}{l^2}\sqrt{\frac{I}{E\rho A}} \qquad (9)$$

And the dimensionless forms of equations (7) and (8), finally the equations related to nonlinear movement of micro-grippers' electrodes based on dimensionless parameters would be calculated as follows:

$$\mu\dot{\eta}_I^{(4)}+\eta_I^{(4)}-\Pi\eta_I''+\ddot{\eta}_I=\frac{SV^2}{(1-\eta_I-\eta_{II})^2}\times$$
$$\left[1+0.265\beta^{-0.75}\left(1-\eta_I\right)^{0.75}+0.53\beta^{-1}\left(1-\eta_I\right)^{0.5}\right] \qquad (10)$$

$$\mu\dot{\eta}_{II}^{(4)}+\eta_{II}^{(4)}-\Pi\eta_{II}''+\ddot{\eta}_{II}=\frac{SV^2}{(1-\eta_I-\eta_{II})^2}\times$$
$$\left[1+0.265\beta^{-0.75}\left(1-\eta_{II}\right)^{0.75}+0.53\beta^{-1}\left(1-\eta_{II}\right)^{0.5}\right] \qquad (11)$$

3- Order reduction method in order to resolve movement equation

Since the differential equation dominating the microbar static form change is in non-linear form, it is impossible to propose an analytic resolution to extract responses. Accordingly, the nonlinear differential equation could be extended using Gallerkin method. Based on his method, microbar static motion could be considered as follows:

$$\eta_I(\xi)=\sum_{k=1}^{n} q_{I,k}\phi_k(\xi),\quad \eta_{II}(\xi)=\sum_{k=1}^{n} q_{II,k}\phi_k(\xi) \qquad (12)$$

Where, $\phi_k\,(k=1,2,\ldots,n)$ are comparative equations and qk is the generalized constituents. In the present research, the comparative functions utilized as the modes of linear microbar bows were taken into consideration. A microbar with one gripped tip and two linear mode endings could be identified through the following:

$$\phi_k(\xi)=A_k\begin{pmatrix}\cosh(\lambda_k\xi)-\cos(\lambda_k\xi)\\ -\dfrac{\sinh(\lambda_k)+\sin(\lambda_k)}{\cosh(\lambda_k)+\cos(\lambda_k)}(\sinh(\lambda_k\xi)-\sin(\lambda_k\xi))\end{pmatrix} \qquad (13)$$

Where, A_k is the fixed mode amount and is calculated through $\left|\phi_k(\xi)\right|=1$. And the parameter λ_k is determined through the equation $\cosh(\lambda_k)\cos(\lambda_k)=-1$. Regarding the configuration of the system under investigations, the primary movement of the microbar is similar to the first bow type model. Therefore, the effect of the first mode would be dominating in share response. Accordingly, in the present study we have used system's first mode approximation and in the method proposed by Gallerkin, only the first mode has been taken into consideration. After applying the method above, the location part of the equations are deleted and movement equations could be expressed in the form of differential equations with couple nonlinear ordinary derivations and after resolving them, the numerical amount gained can extract the system response and can be used to investigate about the effects of different parameters.

4- Justification of the results

First and before studying the effects of parameters and system behavior, in order to make sure of the properness of the numerical methods proposed to resolve the static equations, a silicon microbar is taken into consideration based on reference [18]. The results gained from the resolution of equation (11) for pull-in voltage have been compared with current theoretical and experimental results in reference [18] and table 1. As it can be observed the results calculated are in a very good accordance with the previous results. It should be noted that by the deletion of time constituent of the equation (25-3) and considering $\eta_{II}=0$, the dominant equation will exactly change into the equation dominating the microbar of one end gripped and accordingly we can assess the results in comparison with the results of the microbar of one end gripped affected by electrostatic forces.

Table 1- A comparison of static pull-in voltage for microbar

طول میکروتیر	MEMCAD [18]	مدل انرژی [18]	نتایج تحقیق حاضر
350 μm	20.3 V	20.2 V	20.1 V
	35.8 V	35.4 V	35.3 V
	13.7 V	13.8 V	13.8 V
250 μm	40.1 V	39.5 V	39.5 V
	57.6 V	56.9 V	57.3 V
	33.6 V	33.7 V	33.4 V

5- Results and discussion

After the extraction of equations and assessing the accuracy of the resolution, it's time to study the dynamic behavior of the micro-gripper for different amounts of the system parameters. The geometrical and mechanical characteristics of the micro-grippers under investigations have been represented in tables 2 and 3.

Table 2- Geometrical characteristics of micro-gripper bars

Parameters	Amounts
Length	200 μm
Width	5 μm
Thickness	2.9 μm
Primary distance	4 μm
Air de-electric fixed amount	8.85 pF/m

Table 3- Material characteristics of micro-trigger bars

Parameters	Ceramic	Metal
Material type	alumina	steel
Elasticity module	390 GPa	210 GPa
Poisson coefficient	0.24	0.29
Capacity	3940 Kg/m^3	7850 Kg/m^3
Linear thermal oscillation coefficient	7.2 (10^{-6}/^{0}C)	13 (10^{-6}/^{0}C)

In order to do parameter study, the dimensionless parameters presented in equation (9) are investigated. If we suppose that the time section of the equations is equal to zero, we can study the static movement and inconsistency in micro-grippers if DC voltage is considered to be fixed. In figure 1, the parameter of voltage (V) affected the microbar form change for different voltage amounts. As it can be observed, the lower voltage amounts do not have a considerable effect on microbar form change and as this parameter increases, its effect on microbar form will be greater and in higher voltage amounts, the system will practically become inconsistent and the location change of ends of micro-grippers will be so much that the two ends of them will collide. A counterpart voltage with such a status is technically called a pull-in voltage. Regarding figure 2 in which the distance change of the ending points of micro-gripper has been appointed through the implemented voltage, it can be observed that through the increase of the voltage, the system stiffness will be decreased in a way that it approaches zero in one second and inconsistency will occur or the two ends of the micro-gripper will come into contact. Regarding the results it can be observed that in this status the pull-in voltage equal to 1.38 will be achieved. If we consider this voltage, the micro-gripper will become inconsistent immediately and the two endings will collide and the system performance will be a different one.

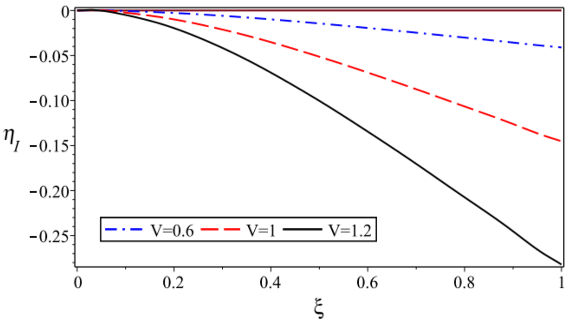


Fig.1. Form change of micro-gripper for different amounts of the voltages utilized

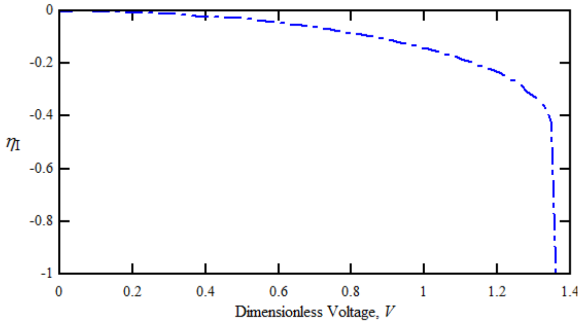


Fig.2. Distance change of micro-gripper for different amounts of the voltages utilized

6- The effect of temperature on inconsistency of micro-gripper in the presence of DC voltage

In this part we deal with studying the effect of temperature considering the two linear and non-linear models of thermal stress affecting the form change and inconsistency of pull-in micro-grippers. In this study, it was presupposed that first the micro-gripper is affected by the environmental temperature of ΔT and then the static DC voltage is enforced on it. In figure 3, the effect of environmental temperature increase on static form change of the micro-grippers has been represented. As it can be observed in the figure, due to the reduction of the primary distance between the microbars which is resulted from environmental temperature increase, the micro-gripper reaches inconsistency in lower voltages and thus as the result of the increase of thermal momentum, the inconsistency voltage will decrease more. Although heat can be used as a stimulating force to move microbars, in some cases it would be necessary to avoid the primary movement of the bars and the reduction of their primary distances by changing the temperature of the environment to pick up some instruments with different sizes.

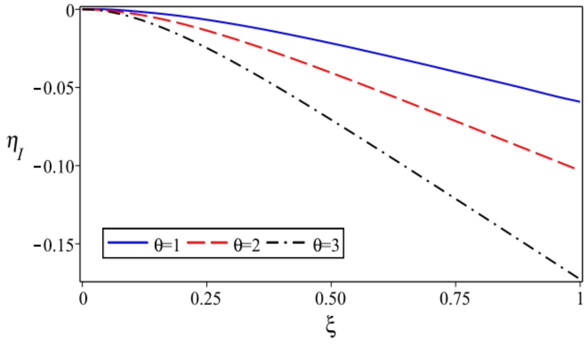


Fig.3. The effect of environment temperature increase on static form change of micro-grippers

In table 4, you can clearly observe the effect of temperature increase on inconsistency voltage load of pull-in systems. Regarding the linear model of thermal stress behavior, when the external voltage v=0.2 is injected into the system, the system will encounter inconsistency when the temperature is $\theta_{cr} = 21.73$, while non-linear thermal stress model will lead to increase critical temperature of the system compared to the linear model and it results in the system reach inconsistency in a temperature of $\theta_{cr} = 31.90$, which is about 32 percent higher than the critical temperature of the linear model. These results show that temperature has a highly considerable effect on consistency behavior of the micro-grippers and it fosters the system inconsistency and considering the frequency of nonlinear thermal stress will be more realistic.

Table 3- The comparison of linear and nonlinear models of thermal stress on pull-in voltage of the system regarding different amounts

θ	V	
	Linear stress-temperature case	*Non-linear stress-temperature case*
0	1.38	1.38
5	1.14	1.16
10	1.09	1.12
15	0.93	1.03
20	0.45	0.78
21.73	0	0.61
31.90	0	0

In figure 4, the changes of bow type load regarding the two linear and nonlinear models for thermal stresses have been compared. Results showed that in lower temperatures, the effect of linear and nonlinear models of thermal stress on critical bow type load system has almost been the same. As the system temperature increases, the nonlinear model which is a more realistic one, can predict the critical system load almost better than the linear model. In this way, in higher temperatures than $\theta = 21.73$, the linear model of thermal stress in the system will be inconsistent, but if the nonlinear model of thermal stress is applied, the system will be consistent up to the temperature of $\theta = 31.9$. These results showed that regarding the lower amounts of the temperature, the effect of linear and nonlinear thermal stress on pull-in voltage will be almost the same and as the temperature increases, the effect of thermal stress theory on pull-in voltage will be more.

In figure 5, the response of the microbar ending of the upper micro-gripper along with fuzzy curve for the DC voltage utilized showed the amount of 0.4 volts. As it can be observed through the results, the voltage increase will lead to increase the range of system fluctuations and the presence of visco-elastic in the system will cause the reduction of system fluctuation range as the time passes. Considering the fuzzy curves of the microbar for the different voltages, it can be observed that when the applied voltage into the system is increased, the speed of the ending position of the microbar increases tremendously. The voltage effect on system equilibrium points can be clearly observed in the following figures.

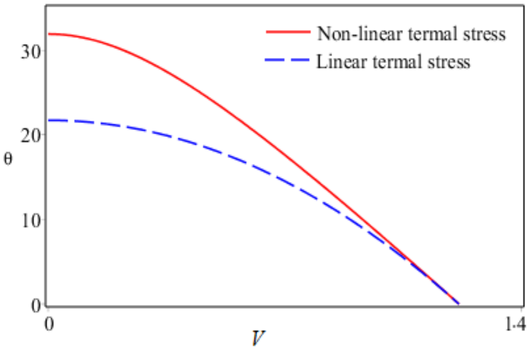
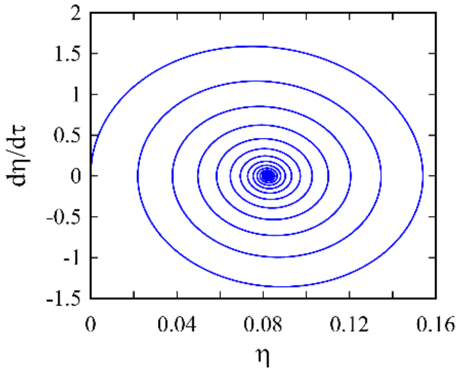


Fig.4. Pull-in voltage changes regarding the two linear and nonlinear models for thermal stress for the amounts of $\lambda_1 = 0.5$ and $\lambda_2 = -5\times10^{-3}$



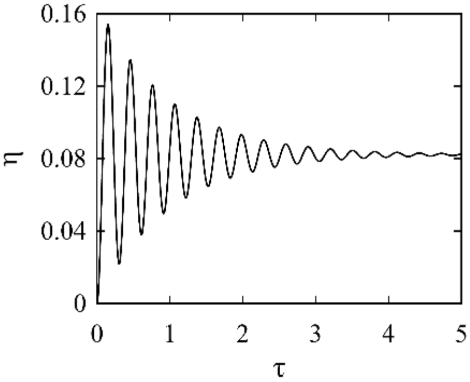


Fig.5. The microbar ending response of the upper bar of the micro-gripper along with the fuzzy curve for the voltage enforced equal to V=0.4V

7- Conclusion

Results of the present research can be summarized as follows:

1) As the voltage increases, the system stiffness decreases in way that in a moment it becomes zero and inconsistency occurs or the two endings of the micro-gripper collide. Regarding the results, it can be observed that in this state the pull-in voltage will be equal to 1.38. For this amount of the voltage, the micro-gripper will immediately become inconsistent and the two endings of its microbars collide and the system performance will change.

2) For the linear model of thermal stress behavior, when the external voltage of V=0.2 is applied, the system temperature of $\theta_{cr} = 21.73$ will cause inconsistency. Meanwhile, the nonlinear thermal stress model will cause the increase of critical system temperature compared to the linear model and it causes the system to become inconsistent when $\theta_{cr} = 31.90$, that is about

32 percents higher than the critical temperature of the linear model.

3) Temperature has a highly considerable effect on consistency behavior of the micro-grippers and it fosters the system inconsistency and regarding the nonlinear frequency of thermal stress is more realistic.

4) Voltage increase leads to increase the system fluctuations range and the presence of visco-elastic in the system will reduce the system fluctuation range as the time passes. Considering the fuzzy microbar curves for different voltage amounts, it can be observed that when the voltage applied for the system increases, the speed of the final position of the microbar will increase considerably.

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