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FGM micro-gripper under electrostatic and intermolecular Van-der Waals forces using modified couple stress theory

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Abstract. In this paper mechanical behavior of the functional gradient materials (FGM) micro-gripper under thermal load and DC voltage is numerically investigated taking into account the effect of intermolecular forces. In contrary to the similar previous works, which have been conducted for homogenous material, here, the FGM material has been implemented. It is assumed that the FGM micro-gripper is made of metal and ceramic and that material properties are changed continuously along the beam thickness according to a given function. The nonlinear governing equations of the static and dynamic deflection of microbeams have been derived using the coupled stress theory. The equations have been solved using the Galerkin based step-by-step linearization method (SSLM). The solution procedure has been evaluated against available data of literature showing good agreement. A parametric study has been conducted, focusing on the combined effects of important parameters included DC voltage, temperature variation, geometrical dimensions and ceramic volume concentration on the dynamic response and stability of the FGM micro-gripper.

Keywords: FGM micro-gripper; electrostatic force; intermolecular force; natural frequency; stability

1. Introduction

With the growing use of micro and nano-scale components in different contexts like Biological Sciences, micro-robots and surgical equipments, application of micro-gripper as a lifting/mowing tool has been increased considerably. The micro-gripper is a particular implementation of a micro manipulation scheme. Micro-gripper designs based on piezoelectric (Haddab *et al*. 2000), electrostatic (Beyeler *et al*. 2007) and electro-thermal (Chronis and Lee 2005) actuators have been presented in the literature. Commonly used measures of performance for these micro actuators are the force/displacement generation capability, power dissipation and the actuation speed (Krecinic *et al*. 2008). Various mechanism such as electrostatic force (Volland *et al*. 2002, Hesselbach *et al*. 2007, Chen *et al*. 2010) piezoelectric (Nah and Zhong 2007, Zubir *et al*. 2009), pneumatic (Bütefisch *et al*. 2002) and electrothermal (Chronis and Lee 2005, Volland *et al*. 2007, Andersen *et al*. 2008, Sardan *et al*. 2008) are used to move the arm of micro-gripper. The electrostatic force is applied in many structures such as micro-resonators (Song *et al*. 2011), micro-pumps (Ng *et al*.

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2004), tunable capacitors (Ogawa *et al*. 2011), micro-switches (Sadeghian *et al*. 2007, Lin and Zhao 2008), micro-actuators (Rezazadeh *et al*. 2006, Parate and Gupta 2011) and micro-mirrors (Hu *et al*. 2010).

The electrostatic force is applied in order to control the gap between the micro-gripper beams precisely. One of the main drawbacks of using electrostatic force is its role in instability of the beams. Indeed, when the DC voltage exceeds from a critical value, the electrostatic force overcomes the elastic restoring force causing instability in the deflection of the beams. This critical value is called the system pull-in voltage.

The electrostatically actuated micro-gripper has been investigated by many researchers (Kim *et al*. 1990, Millet *et al*. 2004, Kawamoto and Tsuji 2011). Wen-Hui and Ya-Pu (2003) have studied the dynamic behavior of nanoscale electrostatic actuators by considering the effect of the van der Waals force. In these investigations, a one degree of freedom lumped parameter model has been used by the researchers. Most of the previously developed micro-grippers cannot be operated in physiological (Chronis and Lee 2005). Electrostatic grippers (Kim 1991) cannot be stimulated in electrolytic media due to solid surface and bulk ions. Thermally driven grippers (Pan and Hsu 1997, Keller 1998) operate at extremely high temperatures and high voltages (Neagu *et al*. 2000). For overcome to this problem the FGM micro-grippers would be a good and effective choice. FGM provides capability to control electrical and thermal specifications of the micro-gripper and prohibit from any undesirable electrical and thermal interactions between the micro-gripper and the medium. So, it would play an essential role in designing micro and nanomaterial sensors in order to manipulate high-temperature and electrical resistance testing technology.

The concept of FGM was first considered in Japan in 1984 during a space plane project. Thereafter FGM, were developed for a wide range of applications, such as automotive industries, space vehicles, biomedical materials, reactor vessels, military applications, semiconductor industry and general structural elements in high thermal environments (Pompe *et al*. 2003, Birman and Byrd 2007, Sadowski *et al*. 2007, Mehrabadi and Mirzaeian 2009, Shariyat 2009, Şimşek 2009, Talha and Singh 2011). Due to its wide application, recently, a huge amount of investigation has been conducted in various engineering fields on the FGM. Application of the FGM in micro and nano systems including microbeams and micro-plates has been addressed by (Hasanyan *et al*. 2010, Ke *et al*. 2010, Taeprasartsit 2011).

Akbarzadeh *et al*. (2011) presented an analytical solution for the mechanical behavior of rectangular plates made of FGM based on the first-order shear deformation theory. Li (2008) studied the static and dynamic behavior of Timoshenko and Euler-Bernoulli FGM beams. Mohammadi-Alasti *et al*. (2011) studied the FGM micro beam behavior under the application of voltage and thermal moment. Using large and small deformation theories, Kang and Li (2009) investigated the mechanical behaviors of a nonlinear FGM cantilever beam subjected to an end force. By using Euler–Bernoulli, Timoshenko and the third order shear deformation beam theories Şimşek (2010) studied the Vibration of a functionally graded simply-supported beam due to a moving mass. Ke *et al*. (2010) provided an exact solution for the equation governing the bending vibration of FGM beam.

As mentioned above, the previous studies are mainly confined to study the mechanical behavior of a micro-grippe made up of homogenous material like steel or Aluminum. In this paper, the study of a classic micro-gripper is extended to the FGM micro-gripper. Under study problem includes a couple of parallel FGM microbeams with one end fixed in a support. During this paper nonlinear equations governing movement of the micro-gripper was derived under the effect of electrostatic force and temperature variation taking into intermolecular Van-der Waals force. The

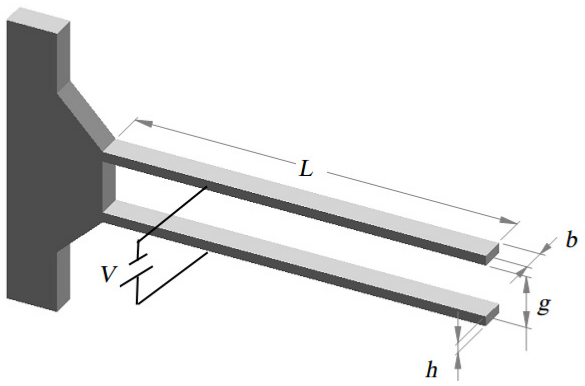


Fig. 1 Schematic of FGM micro-gripper

derived equations were solved using Galerkin and step by step linearization method to reveal the impact of the effective parameters on the static and dynamic behavior of the system.

2. Mathematical modeling

As shown in Fig. 1 is the structure of a typical FGM micro-gripper where the movable beams modeled as a FGM micro-beam of length L, width b, and thickness with an initial gap g_0. The gap between the beams is g, and is influenced by the temperature variation, Van-der Waals forces and the electrostatic force originated from a DC voltage source.

It is assumed that the properties of the FGM micro-beam are varying continuously along the microbeam thickness, using the power law function is as follows (Mohammadi-Alasti *et al*. 2011)

$$E(z) = (P_m)e^{\beta\left(z+\frac{h}{2}\right)}, \quad \rho(z) = (P_m)e^{\beta\left(z+\frac{h}{2}\right)}, \quad \alpha(z) = (P_m)e^{\beta\left(z+\frac{h}{2}\right)},$$
$$\beta = \left(\frac{1}{h}\right)Ln\frac{C_m(P_m) + C_p(P_c)}{P_c} \tag{1}$$

where E, ρ, α indicate module of elasticity, density and the coefficient of linear thermal expansion, respectively, C_m and C_p show the metal and ceramic percentage in the beam thickness, respectively, and z is the thickness coordinate variable.

According to the modified couple stress theory the governing equation of the static deflection of the FGM microbeams obtained as follows (Park and Gao 2006)

$$-(EI + GAl^2)_{FGM}\frac{\partial^2 w}{\partial x^2} = M \tag{2}$$

where G is the shear modulus, l a material length scale parameters. The associated boundary conditions for each FGM microbeams at the fixed end are

$$\frac{\partial w}{\partial x}(0,t) = 0 \qquad w(0,t) = 0 \tag{3}$$

2.1 Nonlinear electrostatic and Van-der Waals force

Considering the first-order fringing field correction, the electrostatic force per unit length and the bending moment are related to each other as (Ramezani, Alasty *et al*. 2006)

$$\frac{\partial^2 M}{\partial x^2} = -F_{ELC} - F_{Van} \tag{4a}$$

where F_{ELC} and F_{Van} are the electric and van der Waals forces per unit length of the beam, respectively. The electrostatic force is obtained as

$$F_{ELC} = \frac{\varepsilon b V^2}{2(g - w_T)^2}, \qquad w_T = w_I + w_{II} \tag{4b}$$

in which ε is the permittivity of air between the two microbeams, V is the applied DC voltage, and w_I and w_{II} are the deflections of the microbeams I and II of the micro-gripper, respectively. The van der Waals force per unit length of the beam is (Israelachvili 2011)

$$F_{Van} = \frac{Hb}{6\pi (g - w_T)^3} \tag{4c}$$

where H is the Hamaker constant.

The equation of transverse motion of the microbeams is

$$(EI + GAl^2)_{FGM} \frac{\partial^4 w}{\partial x^4} + (\rho bh)_{FGM} \frac{\partial^2 w}{\partial t^2} = F_{ELC} - F_{Van} \tag{5}$$

To facilitate theoretical formulations, the following dimensionless quantities are introduced

$$x = \frac{x}{l}, \quad w = \frac{w}{g}, \quad \hat{t} = \frac{t}{t^*}, \quad t^* = \sqrt{\frac{(\rho bhl^4)_{FGM}}{(EI + GAl^2)_m}} \tag{6}$$

Eq. (5) can then be rewritten in dimensionless form as

$$\alpha_1 \frac{\partial^4 w}{\partial \hat{x}^4} + \frac{\partial^2 w}{\partial \hat{t}^2} = \alpha_2 F_e + \alpha_3 F_v \tag{7}$$

in which

$$\alpha_1 = \frac{(EI)_{FGM}}{(EI + GAl^2)_m}, \quad \alpha_2 = \frac{\varepsilon_0 b L^4}{(EI + GAl^2)_m}, \quad \alpha_3 = \frac{Hb}{(EI + GAl^2)_m}$$
$$F_e = \frac{V^2}{(1 - w_T)^2}, \quad F_v = \frac{1}{(1 - w_T)^3} \tag{8}$$

2.2 Temperature variations

In the absence of voltage, electrostatic force is not created, and the bending moment resulted from the external force will be zero. Therefore, the micro-gripper bending moment due to temperature variation will be

$$M = M_T, \tag{9a}$$

$$M_T = \left[\int \left(E\alpha - E\frac{\int E\alpha b dz}{\int E b dz} \right) z b dz \right] \Delta T \tag{9b}$$

The non-dimension governing equation the static deflection of each microbeam of the FGM micro-gripper due to the temperature is expressed as

$$\frac{\partial^2 \hat{w}}{\partial \hat{x}^2} = \alpha_4 M_T, \tag{10a}$$

where

$$\alpha_4 = \frac{-L^2}{g(EI + GAl^2)_{FGM}}. \tag{10b}$$

2.3 Solving the governing equations

2.3.1 FGM micro-gripper under the static nonlinear electrostatic force

The governing equations of static deflections of the microbeams and the associated boundary conditions form a nonlinear ordinary differential equation system whose exact solution is almost impossible. Step-by-step linearization method (SSLM) (Rezazadeh *et al.* 2006) and Galerkin based weighted residual method (Saeedivahdat *et al.* 2010) are therefore used to solve this nonlinear system numerically. To this end, Eq. (7) for microbeams is rearranged as

$$\alpha_1 \frac{d^4 \hat{w}_s}{d\hat{x}^4} - \alpha_2 \left(\frac{V}{1 - w_{T_S}(x)} \right)^2 - \alpha_3 \left(\frac{1}{1 - w_{T_S}(x)} \right)^3 = 0 \tag{11}$$

The SSLM is performed by introducing $\hat{w}_s^k$ as the displacement of the microbeams due to the voltage V^k applied in the k^{th} step and δVas the incremental increase in the applied voltage. Then, the static deflection at the next step, $\hat{w}_s^{k+1}$, due to the corresponding applied voltage, V^{k+1}, can be obtained

$$V^{k+1} = V^k + \delta V \tag{12a}$$

$$w_s^{k+1} = w_s^k + \delta w_s \tag{12b}$$

Therefore, Eq. (9) for the $(k + 1)^{\text{th}}$ step is obtained as

$$\alpha_1 \frac{d^4 \hat{w}_{s_I}^{k+1}}{d\hat{x}^4} - \alpha_2 \left(\frac{\hat{V}^{k+1}}{1 - w_{T_S}^{k+1}} \right)^2 - \alpha_3 \left(\frac{1}{1 - \hat{w}_{T_S}^{k+1}} \right)^3 = 0 \tag{13}$$

Considering a small value of δV, then the deflection variation, $\delta \hat{w}_s$, will be small, too. Using the calculus of variations theory and considering first two terms of the Taylor's expansion, the desired linear equation for the microbeams is obtained as the following

$$\alpha_1 \frac{d^4 \hat{w}_s}{d\hat{x}^4} - \alpha_2 \left[\frac{\partial F_e}{\partial \hat{w}_s} \delta w_s + \frac{\partial F_e}{\partial V} \delta V \right] - \alpha_3 \left[\frac{\partial F_v}{\partial \hat{w}_s} \delta w_s \right] = 0 \tag{14}$$

Here, using the Galerkin based weighted residual method to solve the above equations. To this end, the increment deflection functions of the microbeams are assumed to be as a linear combination of n normal mode shapes of the microbeams

$$\delta w_s(\hat{x}) = \sum_{j=1}^{n} C_j \varphi_j(x) \tag{15}$$

in which $\varphi_j(\hat{x})$ is the j^{th} mode shape and C_j, $j = 1, 2, ..., n$ are unknown constants. By substituting Eq. (15) into Eq. (14), and applying the Galerkin procedure, a set of algebraic equations will be obtained. By solving them, the deflection at any given applied voltage can be determined.

2.3.2 Effect of temperature variations on the FGM micro-gripper

In the absence of the applied voltage, the external force and bending moment on the microbeams will be zero. In this case, the governing equations for the static deflection of the microbeams due to the temperature variations will be expressed as

$$\frac{\partial^2 \hat{w}_s}{\partial \hat{x}^2} = \alpha_4 M_T \tag{16}$$

Static deflection is obtained by integrating the above equations and applying the boundary conditions as

$$w_s = \left(\frac{\alpha_4 M_T}{2} \right) x^2 \tag{17}$$

2.3.3 FGM micro-gripper under the dynamic nonlinear electrostatic force

To study response of the micro-gripper to dynamic loading, a Galerkin-based reduced order model can be used. To achieve a reduced order model, $\hat{w}_d(\hat{x}, \hat{t})$ can be approximated as

$$\hat{w}_d(x,t) = \sum_{j=1}^{n} q_j(t) \varphi_j(x) \tag{18}$$

where $q_j(\hat{t})$ is the generalized coordinate and $\varphi_j(\hat{x})$ is the shape function. By substituting Eq. (18) into Eq. (7) and multiplying by $\varphi_i(\hat{x})$ as the weight function in Galerkin method and then integrating in the length of microbeams, one obtained

$$\sum_{j=1}^{n} \ddot{q}_j(\hat{t}) M_{ij} + \sum_{j=1}^{n} q_j(\hat{t}) K_{ij} = f_i \tag{19}$$

where K and M are the mass and stiffness matrices, respectively and f is the forcing vector that calculated as follows

$$M_{ij} = \int_0^1 \varphi_j(x)\varphi_i(x)dx, \quad K_{ij} = \int_0^1 \varphi_j^{IV}(x)\varphi_i(x)dx, \quad f_i = \int_0^1 (\alpha_2 F_e + \alpha_3 F_v)\varphi_i(x)\,dx \tag{20}$$

3. Numerical results

Unless stated otherwise, the geometry and material parameters of the FGM microbeams considered in this section are given in Tables 1 and 2, respectively, and the permittivity of air, ε_0, is 0.85 pF/m. It is assumed that the FGM micro-gripper is symmetric, so the deflection of each micro-gripper FGM beams under the mentioned conditions will be the same.

Because in the previous investigations only the static pull-in voltage of classic micro-gripper (which is made from a homogenous material) has been studied, therefore, in order to validate the present analysis, the static pull-in voltage results for classic micro-griper are compared with results provided by (Shi *et al*. 1995). Result for the FGM micro-gripper having C_p = 0% and the same geometry and material properties shows very good agreement. The relative difference pull-in voltage percentage between experimentally measured by Shi *et al*. 1995 and theoretically determined is 2.2% (78v for Shi *et al*. 1995 and 79.76v for present work).

3.1 FGM micro-gripper static deflection due to DC voltage

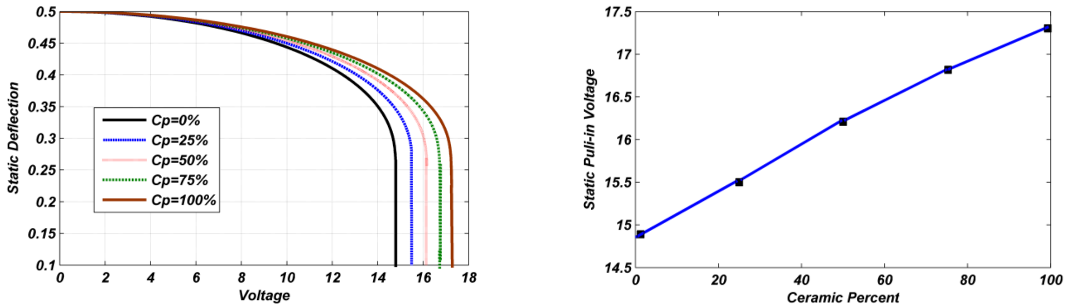
The deflection of the FGM micro-gripper beams free ends against the voltage for the different ceramic percentage is depicted in Fig. 2(a). As it is seen, the deflection gradually increases as the voltage is raised, and after pull-in voltage, the deflection suddenly approaches to maximum value ($\hat{w} = Gap/2 = 0.5$) and the instability occurs. As shown in Fig. 2(b), by increase the ceramic constituent percentage, the bending stiffness of the FGM microbeams is increased, and therefore system deflection due to the applied voltage is decreased, and it reaches pull-in instability later.

Table 1 Geometrical dimensions of the FGM micro-gripper

Geometrical dimensions	Length, L	Thickness, h	Initial gap, g	Width, b
Values	300 μm	2 μm	4 μm	2 μm

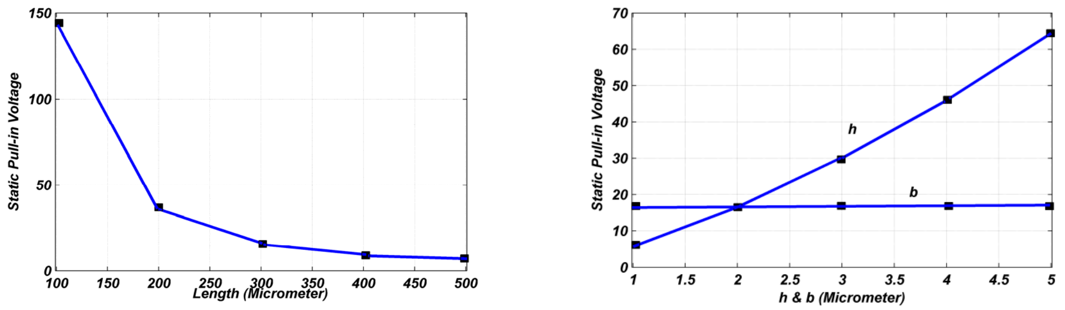
Table 2 Thermo-elastic material properties of the FGM micro-gripper

Material properties	Metal	Ceramic
Material type	Steel	Alumina
Young's modulus, E	210 GPa	390 GPa
Poisson's ratio, v	0.29	0.24
Density, ρ	7850 kg/m^3	3940 kg/m^3
Linear thermal expansion Coefficient, α	13 (10^{-6}/°C)	7.2 (10^{-6}/°C)
Shear modulus G	75 GPa	152 GPa



(a) (b)

Fig. 2 Static response of the FGM microbeams to an applied voltage: (a) free end deflection; and (b) static pull-in voltage against the ceramic percentage



(a) (b)

Fig. 3 The effect of FGM micro-gripper beams geometric dimensions: (a) the length; and (b) thickness and width, on the static pull-in voltage for the ceramic percentage of C_p = 50%

The effect of geometrical parameters of the FGM micro-gripper on the pull-in voltage of microbeams for the case of C_p = 50% is displayed in Fig. 3. It is noted that with an increase in the length of the beams, the free end deflection of the beams increased, and instability occurs at the lower voltages. Moreover, this figure reveals that the width of the FGM micro-gripper beams does not affect the static pull-in voltage and, increasing the thickness cusses to instability occurs in higher voltage.

3.2 Effect of static application of a DC voltage on the stability

Fig. 4 further investigates the effect of initial conditions on the static movement trajectories of the FGM microbeams. According to these figures, the first point is a stable center, while the second one is an unstable saddle node. The stable and unstable branches of the fixed points meet each other at a saddle-node bifurcation point in the state-control space as the applied voltage is increased. The voltage corresponding to the saddle node bifurcation point has a critical value, which is named as static pull-in voltage in MEMS literature. In other words, the microbeam becomes unstable for every initial condition when the applied voltage reaches the static pull-in voltage. Apparently, the position of the substrate shows the behavior of a singular point, and the system velocity in the vicinity of the mentioned point approaches infinity.

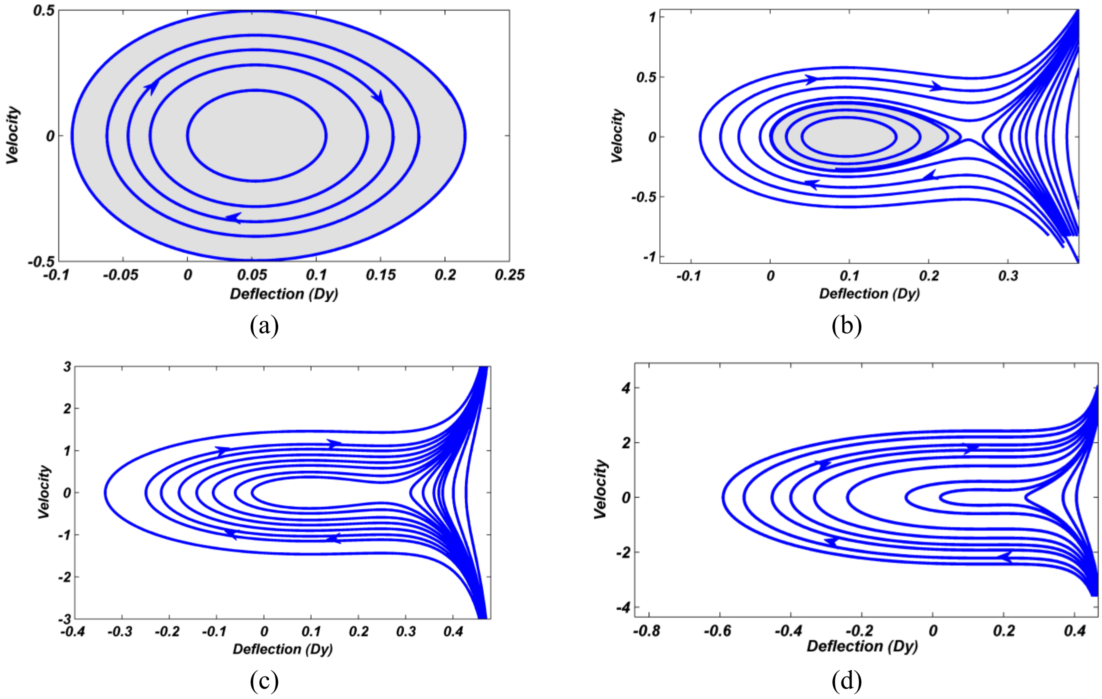


Fig. 4 Movement trajectories of the FGM microbeams for different initial applied voltage: (a) $V = 0v$; (b) $V = 50v$; (c) $V = 62.41v$; (d) $V = 70v$

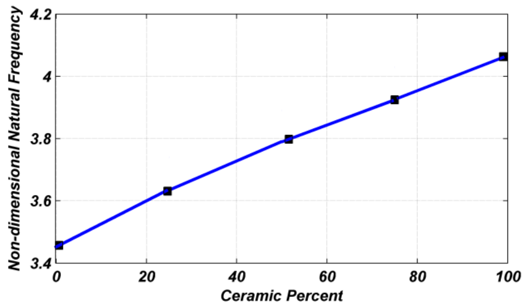


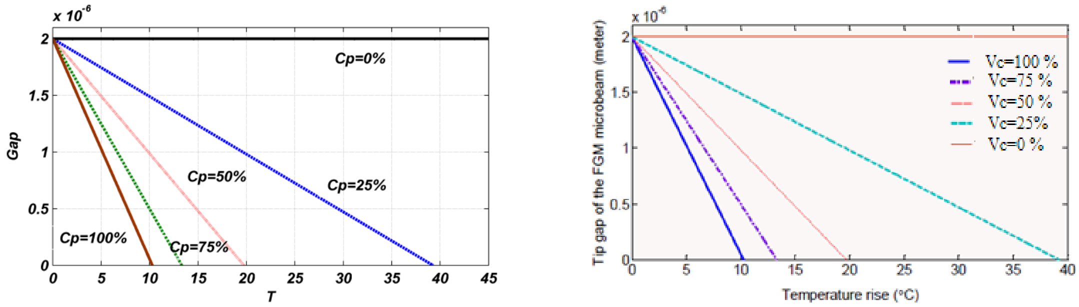
Fig. 5 Non-dimensional natural frequency of the micro-gripper versus the ceramic percentage

3.3 Natural frequency

The value of the non-dimensional natural frequency for different ceramic constituent fractions is depicted in Fig. 5, that with raising C_p, the value of the natural frequency is increased due to growing equivalent FGM microbeams stiffness.

3.4 FGM micro-gripper static deflection due to initial temperature variations

Since FGM micro-gripper was not investigated in recent studies, in the present paper in order to compare the t obtained results, the free end deflection one of the FGM micro-gripper beams was



(a) (b)

Fig. 6 Free end deflection of the FGM microbeam due to applied temperature for different ceramic percentages: (a) present method; and (b) Mohammadi-Alasti *et al*. 2011 work

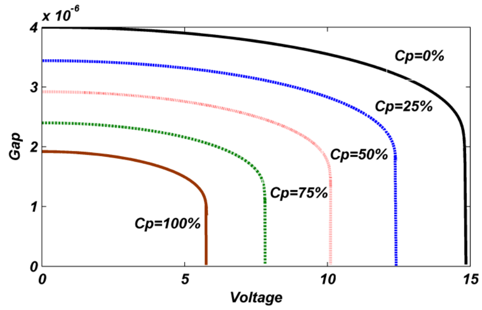
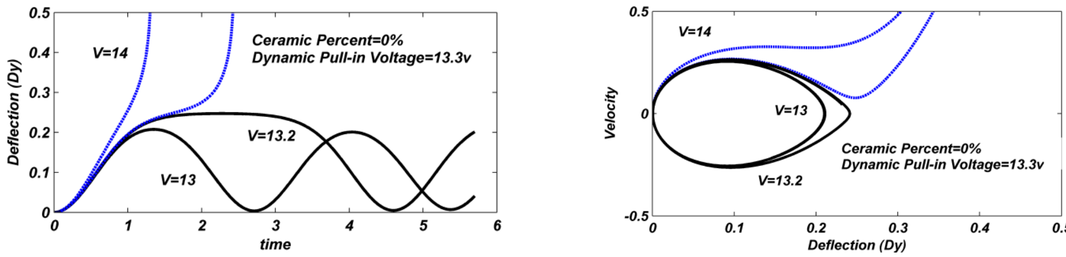


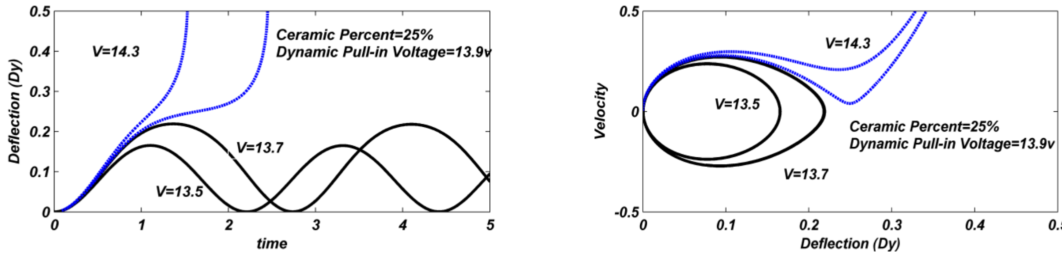
Fig. 7 The gap variation between the free ends of the FGM microbeams of micro-gripper for different ceramic percentages due to the initial temperature variation $\Delta T = 25°$ against the applied DC voltage

compared with those reported in the literature, e.g., Mohammadi-Alasti *et al*. (2011). It was accomplished by considering one of the FGM microbeams in the micro-gripper to be fixed and the variation of the gap due to the deflection of he other FGM beam is studied. For validating the results, the microbeam properties are chosen as the properties in Mohammadi-Alasti *et al*. (2011). Fig. 6 demonstrate the variation FGM micro-gripper beam free end due to the temperature for different ceramic percentages from the presented model and the studied model by Mohammadi-Alasti *et al*. (2011). Comparing the results shows that the presented model predicts the system behavior precisely.

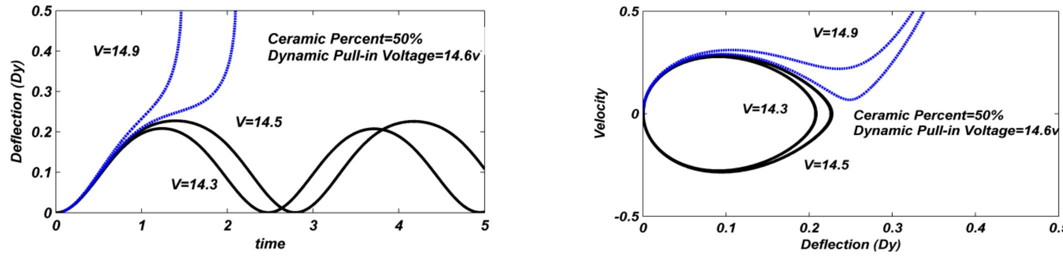
As shown in Fig. (6), increasing the temperature, decrease the gap between the FGM micro-gripper beams and for a given ceramic percentage, the gap reaches zero at a certain temperature. The gap variation due to the temperature changes is because of the thermal expansion increase as ceramic percentage is raised. Therefore, the gap variation is increased due to thermal bending moment that is caused by thermal expansion changes. It is obvious from Fig. 6 that by increasing the ceramic percentage, the gap reaches a certain value at a lower temperature. It is worth to note that for a given temperature, the gap varies proportionally with the ceramic percentage. Also, for the case in which the micro-gripper is made of pure metal, because the thermal expansion in all directions through the beams thickness is the same, then there will be no thermal bending moment in the microbeams, and temperature variation does not affect the gap.



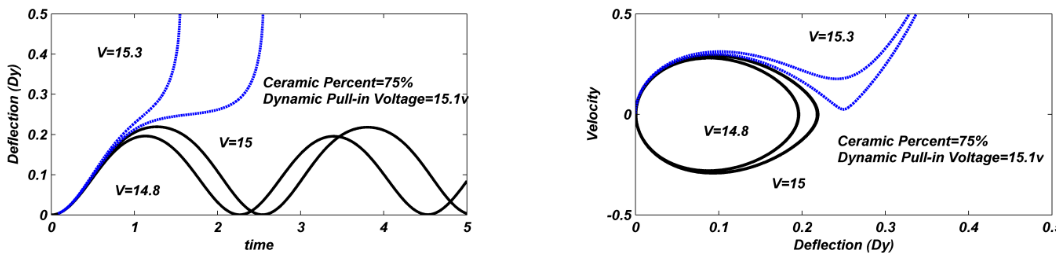
(a)



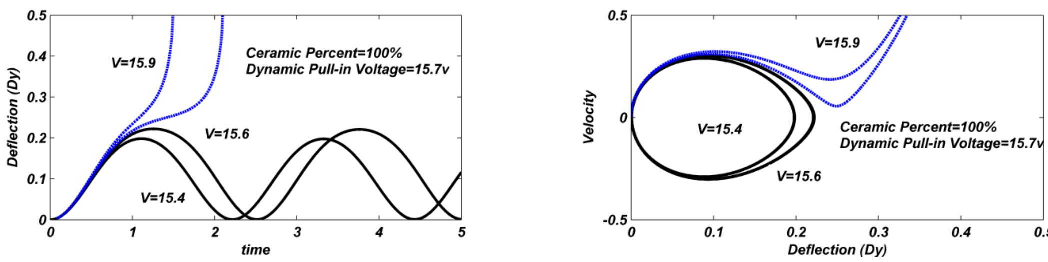
(b)



(c)



(d)



(e)

Fig. 8 Effect of step DC voltages on the dynamic response of the FGM micro-gripper for different ceramic percentage: (a) C_p = 0%; (b) C_p = 25%; (c) C_p = 50%; (d) C_p = 75%; (e) C_p = 100%

In Fig. 7 it is assumed that the FGM micro-gripper has been firstly subjected to the temperature variation of ΔT = 25°, and then the DC voltage is applied statically. By increasing the ceramic percentage for a given temperature variation, the instability is seen to be occurring at lower DC voltages. This happens because the gap value is lower than normal initial state. Although the temperature variation acts as an actuation force and it affects the micro-gripper initial gap and pull-in voltage, one could overcome this deficiency by using $P = P_m e^{\alpha|z|}$ as the feature function for the micro-gripper beams material. The mentioned relation indicates that the beams middle surface is made of pure metal and their upper and lower surfaces have the same combination of ceramic and metal. For such a case, due to the symmetry of the FGM micro-gripper beams material property with respect to their middle surface, there will be no beams deflection due to the temperature variation and therefore the gap will remain constant, as seen Fig. 8.

3.5 Effect of step DC voltage on the FGM micro-gripper dynamic deflection

Plotted in Fig. 8 are curves showing the time history (left hand) and phase portrait (right hand) of FGM micro-gripper beams for different input step DC voltage. It should be mentioned that the instability in the case of applying a step DC voltage is different from its statically application. The saddle node bifurcation, seen in the statically application of DC voltage, is a local stationary bifurcation, and can be analyzed according to locally defined eigenvalues. Applying step DC voltage, periodic orbits experience phenomena that cannot be analyzed according to locally defined eigenvalues. Phenomena like this are called global bifurcations (Kuznetsov 1997).

The metamorphosis of how a periodic orbit becomes a homoclinic orbit at dynamic pull-in voltage is shown in Fig. 8. As a matter of fact, the periodic orbit gets to an end at dynamic pull-in voltage, where a homoclinic orbit is initiated. It means that when the applied voltage approaches dynamic pull-in voltage due to the displacement dependency of the nonlinear electrostatic force, and the equivalent stiffness is declined, period of oscillations tends to infinity. The consequence is a symmetry breaking occurring in motion trajectories. When the periodic orbit collides with a saddle point at dynamic pull-in voltage, a homoclinic bifurcation happens.

4. Conclusions

The pull-in instability and dynamic behavior of FGM micro-gripper under electrostatic and intermolecular Van-de Waals forces is studied in this paper based on Euler–Bernoulli beam theory and coupled stress theory. By extending the methods used to analysis of the mechanical behavior of a classic micro-gripper to a FGM micro-gripper, the nonlinear equations governing the static and dynamic deflection of the FGM micro-gripper due to the DC voltage are derived and solved by using SSLM and Galerkin method. The results show that by increasing the DC voltage, the gap between the free ends of the FGM micro-gripper beams as well as the system natural frequency decreases. It is demonstrated that for a given applied voltage there exist two fixed points over the substrate; the first fixed point is a stable centre, and the second one is an unstable saddle node. It is shown that the system undergoes to an unstable condition through a saddle node bifurcation in the case of statically application of polarization voltage and through a homoclinic bifurcation in the application of a step DC voltage. The corresponding voltages to the saddle node (static pull-in voltage) and homoclinic bifurcation (dynamic pull-in voltage) points were calculated. In addition, the static pull-in voltage of the FGM micro-gripper that is initially subjected to the initial temperature variation decreases by increasing the ceramic percentage, and the instability occurs at lower DC voltage. It should be noted that intermolecular Van-der Waals force does not have considerable effect on the mechanical behavior of the FGM micro-gripper.

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CC

Nomenclature

V	Voltage	w	Deflection
L	Length	M	Bending moment
b	Width	F_{ELC}	Electrostatic force
h	Thickness,	ε_0	Coefficient of electrical permittivity of air
g_0	Initial gap	w_I, w_{II}	Microbeam Deflection
C_m	Metal percentage	w_T	Total deflection
C_p	Ceramic percentage	ΔT	Temperature variation
P_m	Feature of metal	M_T	Thermal bending moment
P_c	Feature of ceramic	$\hat{w}$	Non-dimensional deflection
E	Module of elasticity	$\hat{w}_{s_I}$	Microbeam Static Deflection
I	Area moments of inertia	$\hat{w}_{T_S}$	Static total deflection
C	Constant	φ	Shape function
q	Generalized coordinate	$\hat{w}_d$	Dynamic total deflection