Research Article

Stability Analysis of CNT Based Nano-Actuator Under Magnetic Field and Rippling Deformation

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Abstract

Objective: The widespread use of carbon nanotube-fabricated electromechanical systems has resulted in new operating scenarios for these structures, such as the presence of an external magnetic field. Also, rippling can significantly impact the performance of carbon nanotube-based actuators. These critical phenomena, however, are frequently overlooked in theoretical beam models. This paper simulates the electromagnetic instability of a carbon nano-tube-made actuator subjected to an external magnetic field. As the rippling bending may affect the stability performances of the nano-actuator, the influence of the rippling phenomenon is considered in the governing equation. Also, the impact of van der Waals force is incorporated in the simulation.

Methods: The governing equation of carbon nano-tube-manufactured nano-actuator is developed in terms of bending moment and lateral forces. Rippling is a wavelike deflection of bent carbon nanotubes on their inner arc. This configuration is crucial for large deformations, both globally and locally. The classical linear relationship between the bending and curvature cannot be employed for rippled CNT. Therefore, a modified non-linear curvature-moment relationship is used in the developed model. The impacts of the magnetic field, electrical force and van der Waals attraction are incorporated as lateral loads. The induced transverse load on the carbon nanotube due to a constant longitudinal magnetic field is simulated by using the Maxwell electrodynamics equations. Finally, the constitute equation of the nano-actuator is obtained which is a non-linear ordinary differential equation. A semi-analytical solution based on the Galerkin method is presented to solve the system’s non-linear governing equation.

Results: The proposed model is confirmed by comparing the resulting result to experimental data. Then, the influences of van der Waals interaction, the longitudinal magnetic flux, and rippling bending on the electromagnetic instability parameters of the nano-actuator are studied. The obtained results demonstrate that reveals that the van der Waals force reduces the instability deflection. Moreover, imposing an external magnetic field decreases the instability voltage of the system. Similarly, the instability voltage of the nano-actuator lessens by considering the rippling effect.

Conclusion: A mathematical model is established to study the instability of a CNT-made actuator in a magnetic environment. The model accounts for the longitudinally magnetic field using suitable body
forces and the van der Waals interactions. The proposed model also takes into account the influence of rippling bending. The obtained results demonstrated that both magnetic flux and rippling phenomena reduce the instability voltage of the nano-actuator.

**Keywords:** carbon nanotube, magnetic field, rippling deformation, van der Waals force

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**1 INTRODUCTION**

Due to their unique physical, electrical, and mechanical characteristics, carbon nanotubes (CNTs) have become one of the attractive nano-scale materials in many areas of sciences and industries. CNTs show great potential in various applications, including atomic force microscope (AFM) probes\(^{[34]}\), drug delivery\(^{[2-5]}\), nano-electromechanical system (NEMS) based devices\(^{[26,27]}\), nano-sensors\(^{[10-13]}\), and nano-tweezers\(^{[14-16]}\). Application potentials in nano-fluids have been reported\(^{[17-19]}\).

Mechanical performances of CNT manufactured nano-actuators can be simulated using the molecular dynamic approach\(^{[20,21]}\). Molecular mechanics, on the other hand, necessitates exorbitantly expensive computer resources and is inapplicable to structures with a high number of atoms. Nano-scale continuum models are viable techniques for CNT-based nanostructures simulation to address such insufficiency of molecular dynamics. CNT features exceptional flexibility and exhibits considerable elastic deformation. Hence, the rippling phenomenon can alter the mechanical performance of bent CNTs. However, the classical beam theories are inapplicable in considering the impacts of rippling in the simulation. The bending modulus of cantilever CNTs have been investigated experimentally\(^{[22]}\). Wang and Wang simulated rippling formation and proposed a bending moment-curvature relationship of CNTs\(^{[23]}\). Many researchers have used this model for simulating the rippling phenomenon\(^{[24-28]}\). Soltani et al.\(^{[24]}\) investigated the transverse vibration of single-walled carbon nanotubes by considering the rippling bending. Mehdipour et al.\(^{[29]}\) developed a non-linear beam model for studying the impact of rippling on the free vibration of embedded CNTs. The dynamic performances single-walled CNT manufactured actuators with rippling deformation were investigated in Ref.\(^{[26]}\). In another research, by considering rippling deformation, Sedighi and Farjam explored the dynamic pull-in properties of nano-scale actuators\(^{[27]}\). Under rippling deformation, Ghaffari and Abdelkafi examined the dynamic response of CNT bases sensors in magnetic and thermal conditions\(^{[28]}\).

Extensive industrial applications of CNT manufactured NEMS results in new working environments such as external magnetic flux. Previous experimental studies have revealed that the magnetic field can buckle beams and plates\(^{[29,30]}\). The finite element simulation has also been employed to investigate magnetoelastic buckling of beam-plate\(^{[31]}\). Shih et al.\(^{[32]}\) developed the constitutive relations of a beam with fluctuating transverse magnetic flux. The equation of motion of electromagnetically conducting plates in a magnetic environment was derived in Ref.\(^{[33]}\). Kiani\(^{[34]}\) studied the vibrations of a conducting nanowire surrounded in an elastic medium due to an axial magnetic shock. A nonlocal thermo-magneto elastic model for investigating the dynamic behavior of a nanowire in a magnetic field was presented in Ref.\(^{[35]}\). The stress-driven nonlocal model was also used to study hybrid nanotubes in an external magnetic field\(^{[36]}\). The dynamic stability of nano-sensors was studied by Koochi et al.\(^{[37]}\) by considering the influence of the magnetic field. Yaghoobi and Koochi developed a finite element simulation to investigate the impact of magnetic flux on the electromagnetic instability of nano-wire manufactured tapered nano-tweezers\(^{[38]}\). Khan et al. investigated the impacts of magnetic flux on the heat and mass transfer of a chemically reactive nanofluid\(^{[39]}\) and found that the magnetic field reduced the fluid velocity. Ramezani and Mojra developed a nonlocal couple stress model for analyzing the stability of conveying-nanofluid CNT under magnetic field theory\(^{[40]}\). Mahesh and Harursampath studied the nonlinear deflection of CNT reinforced shells subjected to magnetic fields\(^{[41]}\).

Herein, the instability of a CNT manufactured nano-actuator in a magnetic environment is investigated. As the rippling bending affects the performance of CNTs, the constitutive equation of nano-actuator was developed under the rippling effect. Also, the impact of van der Waals force was incorporated in the simulation. The Galerkin technique was used to solve the non-linear governing equation of the system. Comparison of the acquired findings with the experimental data confirmed the results.

**2 EQUATIONS OF MOTION**

Figure 1 shows a typical nano-actuator made of carbon nanotubes. The CNT’s length and radius are \(L\) and \(R\), respectively. The distance between the ground and the actuated CNT is initially \(g\).
The governing equation of CNT based nano-actuator subjected to external load $F(x)$ can be formulated as:

$$\frac{d^3M}{dx^3} = F(x) \quad (1)$$

where $M$ indicates the bending moment, and $F(x)$ denotes the summation of external loads (i.e., electrical load, the lateral force due to external magnetic flux, and van der Waals force). Using Maxwell electrodynamics equations, the induced load along z-direction of CNT due to a constant longitudinal magnetic field (i.e., $(H_x,0,0)$) can be defined as:

$$F_M = \omega A H_x^2 \frac{d^3W}{dx^3} \quad (2)$$

where $\omega$ is the magnetic permeability, $A$ is the CNT cross-section area, and $W$ represents the transverse deflection of the CNT.

By imposing an external voltage difference between the CNT and graphene sheets, a transverse load acts on CNT. The electrical force ($F_E$) exerting on CNT can be defined by the capacitance model. Hence, the electrostatic force can be explained as:

$$F_E = \frac{\pi \varepsilon_0 V^2}{\sqrt{(g-W+2R)(g-W)} \arccosh \left( \frac{g-W}{R} \right)} \quad (3)$$

where $V$ stands for the applied voltage and $\varepsilon_0$ is the permeability of the vacuum.

For tiny separations, the intermolecular force ($F_{vdW}$) that operates on CNT may be described as follows:

$$F_{vdW} = \frac{C_s \vartheta^2 n^2 N_w R}{d_s (g-W)^4} \quad (4)$$

where $\vartheta$, $d_s$, and $N_w$ are the graphene surface density, the graphene interlayer distance, and the number of graphene layers, respectively. $C_s=15.2 \cdot 10^{-6}$ is carbon-carbon attractive constant.

As mentioned, the rippling phenomena considerably affect the mechanical performances of bent CNTs. Rippling is a wavelike deflection of bent CNTs on their inner arc. This configuration is crucial for large deformations, both globally and locally. The classical linear relationship between the bending and curvature is not applicable for rippled CNT. To overcome this shortage, Wang et al. investigated the curvature-moment relationship of CNTs using a finite element simulation, and adopted a polynomial equation for the rippling deformation:

$$M = EI\kappa(1-aD^3\kappa^2 + bD^4\kappa^4 - cD^6\kappa^6 + dD^8\kappa^8) \quad (5)$$

where $D$ is the mean diameter of CNT and $\kappa$ indicates its bending curvature. Also, $a$, $b$, $c$, and $d$ are cure fitting constants which are determined by Wang et al. as:
By neglecting the higher-order terms, the second derivative of bending moment by considering the rippling effect is obtained as:

$$\frac{d^2W}{dx^2} = EI \left[ \frac{d^4W}{dx^4} - 6aD^2W''W''^2 - 3aD^2 \frac{d^4W}{dx^4} W'' - 3W'' - 9W''W''W'' - 1.5 \frac{d^4W}{dx^4} W''^2 \right]$$  \hspace{1cm} (7)

By substituting Equations (7) and (2-4) in Equation (1), the constitutive equation of nano-actuator is defined as:

$$EL\frac{d^4W}{dx^4} = EL \left[ 6aD^2W''W''^2 + 3aD^2 \frac{d^4W}{dx^4} W'' + 3W'' + 9W''W'' + 1.5 \frac{d^4W}{dx^4} W''^2 \right]$$

$$+ \omega A H^2 W'' + \frac{\pi e_0 V^2}{\sqrt{2 (g - W + 2R)(g - W)}} \arccosh \frac{g - W}{R} d \left( \frac{W - W^f}{g - W} \right)$$  \hspace{1cm} (8)

With the following boundary conditions:

$$W(0) = \frac{dW}{dx}(0) = 0$$  \hspace{1cm} (9)

$$\frac{d^2W}{dx^2}(L) = \frac{d^4W}{dx^4}(L) = 0$$

It is worth noting that Equation (8) can be converted to that explained in Ref\textsuperscript{24} by replacing the summation of electrical, magnetic, and van der Waals force with $F(X)$. By assuming $x = \lambda L$ and $w = W/g$, the non-dimensional equation governed by the deformation of nano-actuator can be explained as:

$$\frac{d^4w}{dx^4} - \frac{d^2w}{dx^2} = \frac{12\lambda \alpha x^4}{\gamma^2} \left[ 2w''w''^2 + \frac{d^4w}{dx^4} w''^2 \right] + 1.5\lambda \alpha^2 \left[ 2w'' + 6w''w'' + \frac{d^4w}{dx^4} w''^2 \right]$$  \hspace{1cm} (10-a)

$$\frac{\eta}{(1 - \omega)^2} \frac{\beta^2}{\sqrt{2 (1-w)^2}} \arccosh \frac{1}{1 + \gamma (1-w)}$$  \hspace{1cm} (10-b)

$$w(0) = w'(0) = 0$$  \hspace{1cm} (10-c)

the dimensionless factors of the above relations are labeled as follows:

$$\gamma = \frac{g}{R} \hspace{1cm} (11-a)$$

$$\alpha = \frac{g}{L} \hspace{1cm} (11-b)$$

$$\beta = \sqrt{\frac{V^2}{g} \frac{\pi e_e}{EI}} \hspace{1cm} (11-c)$$

$$\eta = \frac{C_0 \sigma \pi R H^2}{d_g g^2 EI} \hspace{1cm} (11-d)$$

$$\xi = \frac{\omega A H^2}{EI} \hspace{1cm} (11-e)$$

The parameter $\lambda$, is between zero and one (0 ≤ $\lambda$ ≤1) and governs the importance of the rippling phenomena. For $\lambda$=0 the rippling effect is ignored. However, the rippling bending is at its maximum if $\lambda$ is close to one.
3 SOLUTION

The Galerkin approach facilitates to estimate the solution to boundary value problems. This method approximated the solution based on the weighted residual method:

\[ w(x) = \sum_{i=1}^{n} q_i N_i(x) \]  

(12)

where \( q_i \) represents unknown constants, and \( N_i(x) \) stands for trial functions. The trial function must be a continuous function that meets the boundary requirements over the whole domain.

In the Galerkin method, we employed the linear mode forms of the cantilever nano-beam as trial functions. Cantilever nano-beams have the following mode shapes:

\[ N_i(x) = \cos(\omega_i x) - \cos(\omega_i x) \frac{\cosh(\omega_i x) - \cos(\omega_i x)}{\sinh(\omega_i x) - \sin(\omega_i x)} \]  

(13)

where \( \omega_i \) is the \( i \)th root of the nano-beam’s characteristic equation.

By replacing the approximated solution Equation (12) in Equation (10), using the Taylor expansion for electrical and van der Waals loads, multiplying both sides by \( N_i \), and integrating the obtained relation over the domain, a system of \( n \) algebraic equations was achieved. The unknown parameters can be determined from the following system of the algebraic equations:

\[ \begin{align*}
&-12\pi a^2 \frac{\omega_i^2}{\pi} \left[ \sum_{j=1}^{n} \frac{d^2 N_j}{dx^2} \right] \left( \sum_{j=1}^{n} \frac{d^2 N_j}{dx^2} \right) dx + \int_0^{a} \sum_{j=1}^{n} \frac{d^2 N_j}{dx^2} N_i \left( \sum_{j=1}^{n} \frac{d^2 N_j}{dx^2} \right) dx \\
&-1.5kappa \frac{\omega_i^2}{\pi} \left[ \sum_{j=1}^{n} \frac{d^2 N_j}{dx^2} \right] \left( \sum_{j=1}^{n} \frac{d^2 N_j}{dx^2} \right) dx + 6 \int_0^{a} \sum_{j=1}^{n} \frac{d^2 N_j}{dx^2} N_i \left( \sum_{j=1}^{n} \frac{d^2 N_j}{dx^2} \right) dx \\
&-1.5kappa \frac{\omega_i^2}{\pi} \left[ \sum_{j=1}^{n} \frac{d^2 N_j}{dx^2} \right] \left( \sum_{j=1}^{n} \frac{d^2 N_j}{dx^2} \right) dx = 0 \quad i=1,2,...,n
\end{align*} \]

(14)

where \( n \) indicates the number of assumed terms in the Galerkin solution, and \( A_k \) are defined as:

\[ A_k = \frac{4}{k!} \frac{d^k}{d\omega^k} \left[ \int_{0}^{\infty} \frac{n}{(1-w)^2 + \frac{\beta^2}{\gamma}(1+w) \arccosh^2(1+w)} d\omega \right] \]

(15)

The algebraic system of equations can be numerically solved for investigating the instability threshold of the nano-actuator.

4 RESULTS AND DISCUSSION

The pull-in behavior of a CNT-made nano-actuator surrounded with a magnetic flux has not been studied yet. Therefore, to validate the presented model, the non-linear governing differential equation was solved, neglecting the magnetic field. The obtained results were compared with the experimental data Ke et al. experimentally determined the instability voltage of carbon-made nano-actuator with an initial gap of 3 μm, length of 6.8 μm, and a wire radius of 23.5 nm [7]. Figure 2 shows the nano-actuator gap as a function of applied voltages using our suggested model and those published in Ref [7]. An excellent consistency between the current model and experimental results was obtained.

Figure 3 demonstrates the deformation of nano-actuator for different applied voltage from zero to instability voltage. This Figure illustrates that the CNT deflection increases by enhancing the external voltage. Interestingly, there is an initial deformation when no voltage is applied (i.e., \( \beta=0 \)), which is attributed to van der Waals force. The nano-actuator deformation rises till the pull-in voltage, where instability occurs. It is worth noting that the deformation of CNT at the pull-in point defined the maximum actuation which can be carried out by the nano-actuator.

![Figure 2. The nano-actuator gap as a function of applied voltage: comparison with the experimental data.](image-url)
Figure 3. Deformation of nano-actuator for different applied voltage.

The impact of magnetic flux and van der Waals force on the pull-in characteristics are presented in Figures 4 and 5. Figure 4 shows the instability voltage, whereas Figure 5 shows the deformation at the pull-in position. These Figures investigate a nano-actuator without external magnetic flux and a CNT-manufactured actuator in a magnetic medium. Figure 4 shows that enhancing the van der Waals force results in the reduction of instability voltage. This Figure demonstrates that imposing an external longitudinal magnetic field drives down the instability voltage for all van der Waals force values. Figure 4 illustrates that instability occurs even without electrical load at a critical value of van der Waals force (i.e., $\beta = 0$). This value of the van der Waals parameter is crucial for designing the maximum allowable length and lowest allowable gap of nano-actuators using the following relations:

\[
S_{\text{in}} = \sqrt{\frac{C_\sigma \pi^2 N_p RL^4}{d^4 \eta_k EI}} \quad (16)
\]

\[
L_{\text{max}} = \left( \frac{d^2 \pi^2 E \eta_k}{C_\sigma \pi^2 N_p R} \right) \quad (17)
\]

The results of Figure 4, in combination with Equations (16) and (17), demonstrate that the external magnetic field shortens the maximum length and growth the minimum permissible gap.

Figure 5 shows the influence of magnetic field and van der Waals force on the pull-in deflection of nano-actuator. This Figure reveals that the van der Waals force reduces the instability deflection. However, Figure 5 demonstrates that the impact of magnetic flux on the pull-in deflection is negligible, especially when $\eta < 0.25$.

Figure 6 indicates the influence of the magnetic field, rippling bending, and gap to radius ratio on the instability voltage of the nano-actuator. In this Figure, the pull-in voltage is plotted as a function of geometry parameter $\gamma$ for three different cases (I) neglecting both magnetic field and rippling phenomenon; (II) neglecting magnetic field and considering rippling bending; (III) considering both magnetic flux and rippling effect. This Figure demonstrates that the instability voltage of the nano-actuator increases by enhancing the geometrical parameter $\gamma$. Figure 5 shows that both the rippling phenomenon and the magnetic field reduce the nano-actuator’s instability voltage. While the rippling effect is dominant for lower values of $\gamma$, the magnetic flux is crucial for higher values of $\gamma$.

Figure 5. Impacts of van der Waals force and magnetic field on the pull-in deflection.

Figures 7 and 8 show the influence of the rippling bending on the instability voltage. These Figures show the effect of rippling bending on the instability parameters for various gap to length ratio values. Figures 7 and 8 reveal that for the gap to length ratio less than 0.15, the rippling phenomenon did not considerably alter the instability parameters. However, for larger values of $\alpha$, the rippling effect reduces instability voltage and pull-in deflection.

Figure 6. Impacts of the magnetic field, rippling bending, and geometrical parameter $\gamma$ on the pull-in voltage.
Also, the results of Figures 7 and 8 demonstrate that the effect of rippling bending is more dominant for higher values of the geometrical parameter $\alpha$.

**Figure 7. Impacts of rippling bending on the pull-in voltage.**

**Figure 8. Impacts of rippling bending on the pull-in deflection.**

### 5 CONCLUSION
A mathematical model was established to study the instability of a CNT-made actuator in a magnetic environment. The model accounted for the longitudinally magnetic field using suitable body forces and the van der Waals interactions. The proposed model also took into account the influence of rippling bending. The Galerkin technique was adopted to solve the non-linear governing equation. In addition, the acquired results were compared with the experimental reports. The obtained results showed that the van der Waals force lowered the nano-pull-in actuator’s voltage. The effect of the magnetic field on the pull-in behavior of nano-actuators was investigated, and it was discovered that amplification of the magnetic field lowered the pull-in voltage. The external magnetic field decreases the maximum length and increases the minimum gap of CNT-produced nano-actuators from a design standpoint. The results showed that rippling bending lowered both the instability voltage and the pull-in deflection. Although the rippling effect is minimal at the smaller gap to length ratios, it is dominant at the greater gap to length ratios.

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Not applicable.

### Conflicts of Interest
The author declared no conflicts of interest.

### Author Contribution
Koochi A developed the model, performed the computer programming, prepared the Figures, verified the outputs, wrote the main manuscript, and revised the manuscript.

### Abbreviation List
- **CNT**: Carbon nanotube
- **AFM**: Atomic force microscope
- **NEMS**: Nano-electromechanical system
- $A$, CNT cross-section area
- $A$, Taylor expansion coefficient in the Galerkin method
- $a$, $b$, $c$, $d$, Curve fitting constants
- $C_p$, Carbon-carbon attractive constant
- $D$, Mean diameter of CNT
- $D_g$, Graphene interlayer distance
- $F$, Total external loads
- $F_e$, Electrical force
- $F_m$, Magnetic force
- $F_{vdW}$, van der Waals force
- $g$, Initial gap
- $H$, Magnetic field
- $I(x)$, Trial functions in Galerkin method
- $N$, Number of graphene layers
- $R$, Radius
- $V$, Voltage
- $W$, Deformation in Z direction
- $w$, Dimensionless deformation parameter
- $X$, $Y$, $Z$, Axis of the coordinate system
- $x$, Dimensionless parameter of position along the CNT length
- $\alpha$, Gap to radius ratio
- $\varepsilon_0$, Vacuum permeability
- $\delta$, Graphene surface density
- $\kappa$, Bending curvature
- $\gamma$, Gap to radius ratio
- $\eta$, Dimensionless parameter of van der Waals force
- $\lambda$, Rippling parameter
- $\omega$, Magnetic permeability
- $\omega_i$, The ith root of the nano-beam’s characteristic equation
- $\xi$, Dimensionless parameter of electrical force

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