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Steady-State and Dynamic Response Analysis of a Double-Walled Carbon Nanotube Under Compressive Axial Load

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Abstract

This paper looks into the parametric study of the deflection of double-walled Carbon Nanotubes. Using the Bernoulli-Euler beam theory, a beam model is developed for the transverse displacement of double-walled carbon nanotube under compressive axial load. The model includes the effect of the axial load and also the effect of the van der Waals force that exists between the inner and outer tubes of the carbon nanotube. Expressions for the deflection of the carbon nanotube, a function of both time and space, are derived and solutions are obtained by applying Galerkin's decomposition method (which allows focus on the temporal aspect of the deflection) and Differential Transformation Method (DTM). The solutions are treated using the Cosine After Treatment (CAT) technique to produce converging equations. Graphs of the dynamic response analysis (deflection against time) and steady-state analysis (deflection at certain points on the beam length) and observations are made. The graphs generally describe how the deflection is affected by both temporal and flexural aspects, since it is dependent on both time and space. It is seen from the dynamic response that the inner tube vibrates more than the outer tube does. Also, the number of deflections present along the length of the double-walled carbon nanotube increases as the mode number increases.

Keywords: Dynamic Response; Steady State; Double-Walled Carbon Nanotube; Compressive Axial Load; Galerkin Decomposition Method; Differential Transform Method; Cosine After Treatment.

Nomenclature: F : Compressive Axial Load; V : Shear Force; M : Moment of force; ω : transverse deflection of the tube; x : axial length; A : Cross-sectional Area; ρ : mass density; m : mass; a : acceleration; E : Young's Modulus; I : Second moment of Area; t : time; P_{12} : Van der Waals pressure; c :innertube interaction coefficient; σ_x^0 : axial stress; $(e_0 a)$: Non-local parameter; Ω : Initial static displacement; L : Length of the tube.

Introduction

Carbon Nanotubes were discovered by Iijima in [1], and since then have generated lots of huge activities in most areas of science and engineering due to their unprecedented mechanical, electrical and thermal properties which have led to a lot of resources being put into studies to discover the secrets of these innovative materials. Treacy et al. measured the amplitude of intrinsic thermal vibrations observed in Transmission Electron Microscopy (TEM) and the average value of Young's modulus of Carbon Nanotubes derived from this experimental technique was 1.8 TPa [1]. Poncharal et al. obtained Young's modulus of CNTs which is between 0.7 and 1.3 TPa by electromechanical resonant vibrations [1]. Based on an atomic force microscope (AFM), Wong et al. in 1997 firstly directly measured the stiffness constant of armchair Multi-walled Carbon Nanotubes pinned at one end, from which the value of Young's modulus of Carbon Nanotubes is 1.28 TPa [1]. Salvetat et al. used the AFM for experiment of bending an armchair Multi-walled Carbon Nanotube pinned at each end over a hole and obtained an average modulus value of Carbon Nanotubes of 0.81 TPa [1]. In 1993, Overney et al. calculated Young's modulus of rigid short Single-walled Carbon Nanotubes which is 1.5 TPa, approximately equal to that of graphite [1]. Lu who also used the MD approach, reported that Young's modulus is 1 TPa and claimed that chirality and the number of walls have little effect on the value of Young's modulus [1]. Yao and Lordi made use of a different potential model and obtained Young's modulus of CNTs as 1 TPa [1].

P. Soltani et al.[2] performed a periodic solution for nonlinear vibration of a fluid conveying single-walled Carbon Nanotube showing that the deviation of the nonlinear flow-induced frequency from the linear frequency is considerable when the amplitude, flow velocity and non-local parameter are high while for the CNTs embedded in the mediums of high Pasternak parameters, the nonlinearity of the model does show any effect on the frequency. M. Hosseini et al. [3] performed research on the vibration analysis of single-walled Carbon Nanotube conveying fluid while being subjected to a longitudinal magnetic field with results showing that in the presence of a strong longitudinal magnetic field, the influence of internal fluid flow and nonlocal parameter on the vibrational frequencies of the single-walled CNT can be reduced.

M. Malikan et al. [4] carried out an analysis of damped forced vibration of single-walled carbon nanotubes resting on a viscoelastic foundation in a thermal environment and showed that the higher the value of the nonlocal parameter, the more the effects of abating resonant vibration would be increased in the physical structures of the nanotube. R. Ansari et al. [5] carried out a study on the Torsional vibrational analysis of Carbon Nanotubes based on the Strain gradient theory and Molecular Dynamic simulations and were able to notice that the size effect had a significant role in the vibrational response of nanotubes in small aspect ratios. S. Takahashi et al. [6] performed analysis of flow induced vibrations in closed side branch pipes showing that adding another side branch with an orifice was very effective in suppressing the flow-induced acoustic resonance. M. Malikan et al. [7] performed a buckling analysis of a non-concentric double-walled carbon nanotube and concluded from their results that being off-center in the double-walled CNTs reduces the effects of the inner tube's boundary condition.

X. Yi et al. [8] performed a vibrational analysis of fluid conveying carbon nanotubes based on Nonlocal Timoshenko Beam Theory by Spectral Element method, they were able to conclude that the effect of internal fluid velocity on the natural frequencies of the Single-walled CNT conveying fluid is the same as that of a macro pipe conveying fluid. H. Aminikhah et al. [9] carried out research work on the nonlinear vibrations of Multi-walled Carbon Nanotubes under various boundary conditions applying the Homotopy Perturbation method. Their results showed that the nonlinear vibration frequency of the nanotubes rose quite rapidly with an increase in the amplitude. D. M. Santee et al. [10] performed a research work on the oscillations of a beam on a nonlinear elastic foundation under periodic loads using analytical and semi-analytical perturbation methods to carry out a parametric study. M. Shaban et al. [11] worked on free vibration analysis of carbon nanotubes by using three-dimensional theory of elasticity. S. Zghal et al. [12] did a research work on free vibration analysis of carbon reinforced functionally graded composite shell structures and they did a comparison study of the vibrational behaviour of the various functionally graded composite shell structures. C. Dinckal [13] carried out work on free vibrational analysis of Carbon Nanotubes by using finite element method making use of both the Bernoulli-Euler and Timoshenko beam theories.

S. Oveissi et al. [14] performed longitudinal vibration and stability analysis of carbon nanotubes conveying viscous fluid showing that there is a decrease in the natural frequencies of the system caused by the fluid flowing in the nanotube. S. Kamarian et al. [15] worked on free vibration analysis of conical shells reinforced with agglomerated carbon nanotubes. M. Aydogdu [16] carried out work on axial vibration analysis of carbon nanotubes embedded in an elastic medium using non local elasticity, hence showing that the axial frequencies of the embedded nanotubes are highly overestimated by the classical continuum rod model. C. D. Reddy et al. [17] performed research on free vibration analysis of fluid-conveying single-walled carbon nanotubes. They were able to develop an expression which was used to measure the mass flow rate of the fluid velocities. T. Natsuki [18] engaged in a research work on vibrational analysis of embedded carbon nanotubes using wave propagation approach. S. Asghar et al. [19] carried out the research on non-local effect on the vibration analysis of double-walled carbon nanotubes based on Donnell shell theory which showed the possibility of performing free frequency analysis of DWCNTs using the developed non-local elastic shell model. S.K. Georgantzinos et al. [20] worked on making an efficient numerical model for vibration analysis of single-walled carbon nanotubes giving new natural frequencies and mode shapes for different support conditions. C. M. Wang et al. [21] did a research work on using Timoshenko beam model for analysis of multi-walled carbon nanotubes.

Model Formulation

The Double Elastic beam model: (Figure 1)

By following the Bernoulli-Euler beam theory [22] , the general equation for transverse vibrations of an elastic beam under compressive axial load can be obtained (Figures 2 & 3):

Consider a small slice of the beam as shown above,

$$\sum F = ma = \rho A dx \ddot{\omega}$$

$$\frac{\partial^4 \omega_1}{\partial x^4} + \frac{A_1^2}{I_1}\frac{\partial^2 \omega_1}{\partial t^2} - \frac{\sigma_x^o A_1^2}{EI_1}\frac{\partial^2 \omega_1}{\partial x^2} + \frac{cA_1^2}{EI_1}(\omega_1 - \omega_2) = 0 \qquad (1)$$

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$$\sum M_o = 0$$

$$\frac{\partial^4 \omega_2}{\partial \tilde{x}^4} + \frac{A_2^2}{I_2}\frac{\partial^2 \omega_2}{\partial \tilde{t}^2} - \frac{\sigma_X^O A_2^2}{EI_2}\frac{\partial^2 \omega_2}{\partial \tilde{x}^2} + \frac{cA_2^2}{EI_2}(\omega_2 - \omega_1) = 0 \qquad (2)$$

For small deflections,

$$\sin\theta \simeq \theta = \omega', \sin(\theta + d\theta) \simeq \theta + d\theta = \omega' + \omega'' dx$$

Substitute into (3.1),

$$-\frac{\partial V}{\partial x}dx + \left(F + \frac{\partial F}{\partial x}dx\right)(\omega' + \omega'' dx) - F\omega' = \rho A dx \ddot{\omega}$$

$$\frac{\partial^4 \omega_1}{\partial \tilde{x}^4} + \alpha_1 \frac{\partial^2 \omega_1}{\partial \tilde{t}^2} - \beta_1 \frac{\partial^2 \omega_1}{\partial \tilde{x}^2} + \gamma_1(\omega_1 - \omega_2) = 0 \qquad (3)$$

From (3.2).

$$\frac{\partial M}{\partial x}dx - Vdx = 0$$

$$\frac{\partial^4 \omega_2}{\partial \tilde{x}^4} + \alpha_2 \frac{\partial^2 \omega_2}{\partial \tilde{t}^2} - \beta_2 \frac{\partial^2 \omega_2}{\partial \tilde{x}^2} + \gamma_2(\omega_2 - \omega_1) = 0 \qquad (4)$$

But

$$M = EI\omega''$$

$$\therefore V = \frac{\partial(EI\omega'')}{\partial x}$$

Substitute into (3.3),

$$\frac{\partial^4 \omega_1}{\partial \tilde{x}^4} + (1-(e_0a)^2\nabla^2)\alpha_1 \frac{\partial^2 \omega_1}{\partial \tilde{t}^2} - (1-(e_0a)^2\nabla^2)\beta_1 \frac{\partial^2 \omega_1}{\partial \tilde{x}^2} + (1-(e_0a)^2\nabla^2)\gamma_1(\omega_1 - \omega_2) = 0 \qquad (5)$$

Which can be rearranged to give,

$$\frac{\partial^4 \omega_2}{\partial \tilde{x}^4} + (1-(e_0a)^2\nabla^2)\alpha_2 \frac{\partial^2 \omega_2}{\partial \tilde{t}^2} - (1-(e_0a)^2\nabla^2)\beta_2 \frac{\partial^2 \omega_2}{\partial \tilde{x}^2} + (1-(e_0a)^2\nabla^2)\gamma_2(\omega_2 - \omega_1) = 0 \qquad (6)$$

Also, since $\boldsymbol{\omega}$ is a function of both the axial coordinate, x , and the time, t, hence.

$$\omega' = \frac{\partial\omega}{\partial x}, \dot{\omega} = \frac{\partial\omega}{\partial t}$$

However, for double-walled Carbon Nanotubes, it is known that the presence of the innertube Van der Waals forces is one major distinguishing factor from traditional single-walled nanotubes. Assuming that both inner and outer tubes possess the same material constants [23-25], Eq. then becomes

$$\frac{\partial^4 \omega_1}{\partial \tilde{x}^4} + \alpha_1 \frac{\partial^2 \omega_1}{\partial \tilde{t}^2} - \alpha_1 (e_0a)^2 \frac{\partial^4 \omega_1}{\partial \tilde{x}^2 \partial \tilde{t}^2} - \beta_1 \frac{\partial^2 \omega_1}{\partial \tilde{x}^2} + \beta_1 (e_0a)^2 \frac{\partial^4 \omega_1}{\partial \tilde{x}^4} + \gamma_1(\omega_1 - \omega_2) - \gamma_1 (e_0a)^2 \frac{\partial^2(\omega_1 - \omega_2)}{\partial \tilde{x}^2} = 0 \qquad (7)$$

$$\frac{\partial^4 \omega_2}{\partial \tilde{x}^4} + \alpha_2 \frac{\partial^2 \omega_2}{\partial \tilde{t}^2} - \alpha_2 (e_0a)^2 \frac{\partial^4 \omega_2}{\partial \tilde{x}^2 \partial \tilde{t}^2} - \beta_2 \frac{\partial^2 \omega_2}{\partial \tilde{x}^2} + \beta_2 (e_0a)^2 \frac{\partial^4 \omega_2}{\partial \tilde{x}^4} \qquad (8)$$

where the subscripts 1 and 2 are used to indicate the quantities associated with the inner and outer tubes respectively, and P_{12} represents the Van der Waals pressure per unit axial length exerted on the inner tube by the outer tube.

By considering the Lennard-Jones model, the Van der Waals pressure at any point between the two tubes is given as a linear function of the jump in deflection at that point, which is expressed as

$$P_{12} = c(\omega_2 - \omega_1)$$

Where c is the innertube interaction coefficient per unit length, which is estimated by,

$$c = \frac{320(2R_1)}{0.16d^2}$$

Where R_1 is the radius of the inner tube and d = 0.142nm.

Thus, the equation of the model can then be written as:

$$\varepsilon_1(t) = \Omega_1 - \left(\frac{K_1\Omega_1 + J_1\Omega_2}{2M_1}\right)t^2 + \frac{M_2K_1(K_1\Omega_1 + J_1\Omega_2) + M_1J_1(K_2\Omega_2 + J_2\Omega_1)}{24M_1^2M_2}t^4 + \frac{\dfrac{J_1\left(-\dfrac{J_2(J_1\Omega_2 + K_1\Omega_1)}{2M_1} - \dfrac{K_2(J_2\Omega_1 + K_2\Omega_2)}{2M_2}\right)}{12M_2} + \dfrac{K_1\left(-\dfrac{J_1(J_2\Omega_1 + K_2\Omega_2)}{2M_2} - \dfrac{K_1(J_1\Omega_2 + K_1\Omega_1)}{2M_1}\right)}{12M_1}}{30M_1}t^6 \qquad (9)$$

$$\varepsilon_2(t) = \Omega_2 - \left(\frac{K_2\Omega_2 + J_2\Omega_1}{2M_2}\right)t^2 + \frac{M_1K_2(K_2\Omega_2 + J_2\Omega_1) + M_2J_2(K_1\Omega_1 + J_1\Omega_2)}{24M_2^2M_1}t^4 + \frac{\dfrac{J_2\left(-\dfrac{J_1(J_2\Omega_1 + K_2\Omega_2)}{2M_2} - \dfrac{K_1(J_1\Omega_2 + K_1\Omega_1)}{2M_1}\right)}{12M_1} + \dfrac{K_2\left(-\dfrac{J_2(J_1\Omega_2 + K_1\Omega_1)}{2M_1} - \dfrac{K_2(J_2\Omega_1 + K_2\Omega_2)}{2M_2}\right)}{12M_2}}{30M_2}t^6 \qquad (10)$$

These two equations describe the free transverse vibrations of double-walled carbon nanotubes under compressive axial load.

Analytical Solution to Model

Non-dimensionalizing the equations

The Non-dimensionalized forms of the equations are:

$$\frac{d^4 \omega_1}{d\tilde{x}^4} + \frac{A_1^2}{I_1}\frac{d^2 \omega_1}{d\tilde{t}^2} - \frac{\sigma_X^O A_1^2}{EI_1}\frac{d^2 \omega_1}{d\tilde{x}^2} + \frac{cA_1^2}{EI_1}(\omega_1 - \omega_2) = 0$$

$$\frac{d^4 \omega_2}{d\tilde{x}^4} + \frac{A_2^2}{I_2}\frac{d^2 \omega_2}{d\tilde{t}^2} - \frac{\sigma_X^O A_2^2}{EI_2}\frac{d^2 \omega_2}{d\tilde{x}^2} + \frac{cA_2^2}{EI_2}(\omega_2 - \omega_1) = 0$$

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Which then becomes:

$$\frac{\partial^4\omega_1}{\partial\tilde{x}^4}+\alpha_1\frac{\partial^2\omega_1}{\partial\tilde{t}^2}-\beta_1\frac{\partial^2\omega_1}{\partial\tilde{x}^2}+\gamma_1(\omega_1-\omega_2)=0 \quad (11)$$

$$\frac{\partial^4\omega_2}{\partial\tilde{x}^4}+\alpha_2\frac{\partial^2\omega_2}{\partial\tilde{t}^2}-\beta_2\frac{\partial^2\omega_2}{\partial\tilde{x}^2}+\gamma_2(\omega_2-\omega_1)=0 \quad (12)$$

Where;

$$\alpha_1=\frac{A_1^2}{I_1},\alpha_2=\frac{A_2^2}{I_2}$$

$$\beta_1=\frac{\sigma_x^o A_1^2}{EI_1},\beta_2=\frac{\sigma_x^o A_2^2}{EI_2}$$

$$\gamma_1=\frac{cA_1^2}{EI_1},\gamma_2=\frac{cA_2^2}{EI_2}$$

Non-local theory

In order to fully represent the model as a nanostructure and set it apart from the macrotubes (larger, normal sized tubes), the Eringen's non-local theory is used. Eq. (11) and (12) then become.

$$\frac{\partial^4\omega_1}{\partial\tilde{x}^4}+(1-(e_0a)^2\nabla^2)\alpha_1\frac{\partial^2\omega_1}{\partial\tilde{t}^2}-(1-(e_0a)^2\nabla^2)\beta_1\frac{\partial^2\omega_1}{\partial\tilde{x}^2}+(1-(e_0a)^2\nabla^2)\gamma_1(\omega_1-\omega_2)=0 \quad (13)$$

$$\frac{\partial^4\omega_2}{\partial\tilde{x}^4}+(1-(e_0a)^2\nabla^2)\alpha_2\frac{\partial^2\omega_2}{\partial\tilde{t}^2}-(1-(e_0a)^2\nabla^2)\beta_2\frac{\partial^2\omega_2}{\partial\tilde{x}^2}+(1-(e_0a)^2\nabla^2)\gamma_2(\omega_2-\omega_1)=0 \quad (14)$$

And with further simplifying.

$$\frac{\partial^4\omega_1}{\partial\tilde{x}^4}+\alpha_1\frac{\partial^2\omega_1}{\partial\tilde{t}^2}-\alpha_1(e_0a)^2\frac{\partial^4\omega_1}{\partial\tilde{x}^2\partial\tilde{t}^2}-\beta_1\frac{\partial^2\omega_1}{\partial\tilde{x}^2}+\beta_1(e_0a)^2\frac{\partial^4\omega_1}{\partial\tilde{x}^4} \quad (15)$$
$$+\gamma_1(\omega_1-\omega_2)-\gamma_1(e_0a)^2\frac{\partial^2(\omega_1-\omega_2)}{\partial\tilde{x}^2}=0$$

$$\frac{\partial^4\omega_2}{\partial\tilde{x}^4}+\alpha_2\frac{\partial^2\omega_2}{\partial\tilde{t}^2}-\alpha_2(e_0a)^2\frac{\partial^4\omega_2}{\partial\tilde{x}^2\partial\tilde{t}^2}-\beta_2\frac{\partial^2\omega_2}{\partial\tilde{x}^2}+\beta_2(e_0a)^2\frac{\partial^4\omega_2}{\partial\tilde{x}^4} \quad (16)$$
$$+\gamma_2(\omega_2-\omega_1)-\gamma_2(e_0a)^2\frac{\partial^2(\omega_2-\omega_1)}{\partial\tilde{x}^2}=0$$

Galerkin's decomposition Method

Applying Galerkin's decomposition method, in which $\omega(x,t)=\varepsilon(t).\phi(x)$ to Eq. (15) and (16), taking the Eq. (15) first,

Term 1 becomes:

$$\int_0^1\frac{d^4\omega_1}{d\tilde{x}^4}.\phi(x)d\tilde{x}$$

$$=\int_0^1\frac{d^4(\varepsilon_1(t).\phi(x))}{d\tilde{x}^4}.\phi(x)d\tilde{x}$$

$$=\left(\int_0^1\phi(x).\frac{d^4\phi(x)}{d\tilde{x}^4}d\tilde{x}\right)\varepsilon_1(t)$$

Term 2: (17)

$$\int_0^1\alpha_1\frac{d^2\omega_1}{d\tilde{t}^2}.\phi(x)d\tilde{x}$$

$$=\int_0^1\alpha_1\frac{d^2(\varepsilon_1(t).\phi(x))}{d\tilde{t}^2}.\phi(x)d\tilde{x}$$

$$=\left(\int_0^1\alpha_1\phi^2(x)d\tilde{x}\right)\frac{d^2\varepsilon_1(t)}{d\tilde{t}^2}$$

Term 3: (18)

$$\int_0^1\alpha_1(e_0a)^2\frac{d^4\omega_1}{d\tilde{x}^2d\tilde{t}^2}.\phi(x)d\tilde{x}$$

$$=\int_0^1\alpha_1(e_0a)^2\frac{d^4(\varepsilon_1(t).\phi(x))}{d\tilde{x}^2d\tilde{t}^2}.\phi(x)d\tilde{x}$$

$$=\left(\int_0^1\alpha_1(e_0a)^2\phi(x)\frac{d^2\phi(x)}{d\tilde{x}^2}d\tilde{x}\right)\frac{d^2\varepsilon_1(t)}{d\tilde{t}^2}$$

Term 4: (19)

$$\int_0^1\beta_1\frac{d^2\omega_1}{d\tilde{x}^2}.\phi(x)d\tilde{x}$$

$$=\int_0^1\beta_1\frac{d^2(\varepsilon_1(t).\phi(x))}{d\tilde{x}^2}.\phi(x)d\tilde{x}$$

$$=\left(\int_0^1\beta_1\phi(x)\frac{d^2\phi(x)}{d\tilde{x}^2}d\tilde{x}\right)\varepsilon_1(t) \quad (20)$$

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Term 5:

$$\int_0^1 \beta_1 (e_0 a)^2 \frac{d^4 \omega_1}{d\tilde{x}^4}.\phi(x) d\tilde{x}$$

$$= \int_0^1 \beta_1 (e_0 a)^2 \frac{d^4 (\varepsilon_1(t).\phi(x))}{d\tilde{x}^4}.\phi(x) d\tilde{x}$$

$$= \left(\int_0^1 \beta_1 (e_0 a)^2 \phi(x) \frac{d^4 \phi(x)}{d\tilde{x}^4} d\tilde{x} \right) \varepsilon_1(t) \quad (21)$$

Term 6:

$$\int_0^1 \gamma_1 (\omega_1 - \omega_2).\phi(x) d\tilde{x}$$

$$= \int_0^1 \gamma_1 ([\varepsilon_1(t).\phi(x)] - [\varepsilon_2(t).\phi(x)]).\phi(x) d\tilde{x}$$

$$= \left(\int_0^1 \gamma_1 \phi^2(x) d\tilde{x} \right) (\varepsilon_1(t) - \varepsilon_2(t)) \quad (22)$$

Term 7:

$$\int_0^1 \gamma_1 (e_0 a)^2 \frac{d^2 (\omega_1 - \omega_2)}{d\tilde{x}^2}.\phi(x) d\tilde{x}$$

$$= \int_0^1 \gamma_1 (e_0 a)^2 \frac{d^2 ([\varepsilon_1(t).\phi(x)] - [\varepsilon_2(t).\phi(x)])}{d\tilde{x}^2}.\phi(x) d\tilde{x}$$

$$= \left(\int_0^1 \gamma_1 (e_0 a)^2 \phi(x) \frac{d^2 \phi(x)}{d\tilde{x}^2} d\tilde{x} \right) (\varepsilon_1(t) - \varepsilon_2(t)) \quad (23)$$

∴ The equation for the inner tube becomes.

$$\left(\int_0^1 \phi(x).\frac{d^4 \phi(x)}{d\tilde{x}^4} d\tilde{x} \right) \varepsilon_1(t) + \left(\int_0^1 \alpha_1 \phi^2(x) d\tilde{x} \right) \frac{d^2 \varepsilon_1(t)}{d\tilde{t}^2}$$

$$- \left(\int_0^1 \alpha_1 (e_0 a)^2 \phi(x) \frac{d^2 \phi(x)}{d\tilde{x}^2} d\tilde{x} \right) \frac{d^2 \varepsilon_1(t)}{d\tilde{t}^2} - \left(\int_0^1 \beta_1 \phi(x) \frac{d^2 \phi(x)}{d\tilde{x}^2} d\tilde{x} \right) \varepsilon_1(t) + \left(\int_0^1 \beta_1 (e_0 a)^2 \phi(x) \frac{d^4 \phi(x)}{d\tilde{x}^4} d\tilde{x} \right) \varepsilon_1(t)$$

$$+ \left(\int_0^1 \gamma_1 \phi^2(x) d\tilde{x} \right) (\varepsilon_1(t) - \varepsilon_2(t)) - \left(\int_0^1 \gamma_1 (e_0 a)^2 \phi(x) \frac{d^2 \phi(x)}{d\tilde{x}^2} d\tilde{x} \right) (\varepsilon_1(t) - \varepsilon_2(t)) = 0 \quad (24)$$

which can re-written as,

$$\left(\int_0^1 \left[\alpha_1 \phi^2(x) - \alpha_1 (e_0 a)^2 \phi(x) \frac{d^2 \phi(x)}{d\tilde{x}^2} \right] d\tilde{x} \right) \ddot{\varepsilon}_1(t)$$

$$+ \left(\int_0^1 \left[\phi(x).\frac{d^4 \phi(x)}{d\tilde{x}^4} + \beta_1 (e_0 a)^2 \phi(x) \frac{d^4 \phi(x)}{d\tilde{x}^4} + \gamma_1 \phi^2(x) - \beta_1 \phi(x) \frac{d^2 \phi(x)}{d\tilde{x}^2} - \gamma_1 (e_0 a)^2 \phi(x) \frac{d^2 \phi(x)}{d\tilde{x}^2} \right] d\tilde{x} \right) \varepsilon_1(t)$$

$$+ \left(\int_0^1 \left[\gamma_1 (e_0 a)^2 \phi(x) \frac{d^2 \phi(x)}{d\tilde{x}^2} - \gamma_1 \phi^2(x) \right] d\tilde{x} \right) \varepsilon_2(t) = 0 \quad (25)$$

Hence, the equation for the outer tube is now written as,

$$\left(\int_0^1 \left[\alpha_2 \phi^2(x) - \alpha_2 (e_0 a)^2 \phi(x) \frac{d^2 \phi(x)}{d\tilde{x}^2} \right] d\tilde{x} \right) \ddot{\varepsilon}_2(t)$$

$$+ \left(\int_0^1 \left[\phi(x).\frac{d^4 \phi(x)}{d\tilde{x}^4} + \beta_2 (e_0 a)^2 \phi(x) \frac{d^4 \phi(x)}{d\tilde{x}^4} + \gamma_2 \phi^2(x) - \beta_2 \phi(x) \frac{d^2 \phi(x)}{d\tilde{x}^2} - \gamma_2 (e_0 a)^2 \phi(x) \frac{d^2 \phi(x)}{d\tilde{x}^2} \right] d\tilde{x} \right) \varepsilon_2(t)$$

$$+ \left(\int_0^1 \left[\gamma_2 (e_0 a)^2 \phi(x) \frac{d^2 \phi(x)}{d\tilde{x}^2} - \gamma_2 \phi^2(x) \right] d\tilde{x} \right) \varepsilon_1(t) = 0 \quad (26)$$

Eq. (25) and (26) can be compared with the equation of motion, which is written as,

$$M_1 \ddot{\varepsilon}_1(t) + K_1 \varepsilon_1(t) + J_1 \varepsilon_2(t) = 0 \quad (27)$$

$$M \ \ddot{\varepsilon}_2(t) + K_2 \varepsilon_2(t) + J_2 \varepsilon_1(t) = 0 \quad (28)$$

Where.

$$M_1 = \int_0^1 \left[\alpha_1 \phi^2(x) - \alpha_1 (e_0 a)^2 \phi(x) \frac{d^2 \phi(x)}{d\tilde{x}^2} \right] d\tilde{x}, M_2 = \int_0^1 \left[\alpha_2 \phi^2(x) - \alpha_2 (e_0 a)^2 \phi(x) \frac{d^2 \phi(x)}{d\tilde{x}^2} \right] d\tilde{x}$$

$$K_1 = \int_0^1 \left[\phi(x).\frac{d^4 \phi(x)}{d\tilde{x}^4} + \beta_1 (e_0 a)^2 \phi(x) \frac{d^4 \phi(x)}{d\tilde{x}^4} + \gamma_1 \phi^2(x) - \beta_1 \phi(x) \frac{d^2 \phi(x)}{d\tilde{x}^2} - \gamma_1 (e_0 a)^2 \phi(x) \frac{d^2 \phi(x)}{d\tilde{x}^2} \right] d\tilde{x}$$

$$K_2 = \int_0^1 \left[\phi(x).\frac{d^4 \phi(x)}{d\tilde{x}^4} + \beta_2 (e_0 a)^2 \phi(x) \frac{d^4 \phi(x)}{d\tilde{x}^4} + \gamma_2 \phi^2(x) - \beta_2 \phi(x) \frac{d^2 \phi(x)}{d\tilde{x}^2} - \gamma_2 (e_0 a)^2 \phi(x) \frac{d^2 \phi(x)}{d\tilde{x}^2} \right] d\tilde{x}$$

$$J_1 = \int_0^1 \left[\gamma_1 (e_0 a)^2 \phi(x) \frac{d^2 \phi(x)}{d\tilde{x}^2} - \gamma_1 \phi^2(x) \right] d\tilde{x}, J_2 = \int_0^1 \left[\gamma_2 (e_0 a)^2 \phi(x) \frac{d^2 \phi(x)}{d\tilde{x}^2} - \gamma_2 \phi^2(x) \right] d\tilde{x}$$

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Solution of the model using Differential Transformation Method (DTM):

Applying DTM,

$$M_1\ddot{\varepsilon}_1(t)+K_1\varepsilon_1(t)+J_1\varepsilon_2(t)=0$$

Becomes,

$$M_1\left(k+1\right)\left(k+2\right)\varepsilon_{1[k+2]}+K_1\varepsilon_{1[k]}+J_1\varepsilon_{2[k]}=0$$

$$\therefore \varepsilon_{1[k+2]}=-\left(\frac{K_1\varepsilon_{1[k]}+J_1\varepsilon_{2[k]}}{M_1\left(k+1\right)\left(k+2\right)}\right) \quad (29)$$

$$\varepsilon_{2[k+2]}=-\left(\frac{K_2\varepsilon_{2[k]}+J_2\varepsilon_{1[k]}}{M_2\left(k+1\right)\left(k+2\right)}\right) \quad (30)$$

When k=0.

$$\varepsilon_{1[2]}=-\left(\frac{K_1\varepsilon_{1[0]}+J_1\varepsilon_{2[0]}}{2M_1}\right) \quad (31)$$

$$\varepsilon_{2[2]}=-\left(\frac{K_2\varepsilon_{2[0]}+J_2\varepsilon_{1[0]}}{2M_2}\right) \quad (32)$$

But

$$\varepsilon_{1[0]}=\Omega_1\cos\lambda t$$

And

$$\varepsilon_{2[0]}=\Omega_2\cos\lambda t$$

where Ω_1 and Ω_2 are the static displacements of the inner and outer tubes respectively.

At initial condition, t = 0;

$$\varepsilon_{1[0]}=\Omega_1$$

$$\varepsilon_{2[0]}=\Omega_2$$

Differentiating both equations with respect to t and then applying DTM gives.

$$\left(k+1\right)\varepsilon_{1[k+1]}=0$$

$$\left(k+1\right)\varepsilon_{2[k+1]}=0$$

When k =0;

$$\varepsilon_{1[1]}=0\text{ , }\varepsilon_{2[1]}=0$$

Therefore,

$$\varepsilon_{1[2]}=-\left(\frac{K_1\Omega_1+J_1\Omega_2}{2M_1}\right) \quad (33)$$

$$\varepsilon_{2[2]}=-\left(\frac{K_2\Omega_2+J_2\Omega_1}{2M_2}\right) \quad (34)$$

When k =1;

$$\varepsilon_{1[3]}=0 \quad (35)$$

$$\varepsilon_{2[3]}=0 \quad (36)$$

When k =2;

$$\varepsilon_{1[4]}=\frac{M_2K_1\left(K_1\Omega_1+J_1\Omega_2\right)+M_1J_1\left(K_2\Omega_2+J_2\Omega_1\right)}{24M_1^2M_2} \quad (37)$$

$$\varepsilon_{2[4]}=\frac{M_1K_2\left(K_2\Omega_2+J_2\Omega_1\right)+M_2J_2\left(K_1\Omega_1+J_1\Omega_2\right)}{24M_2^2M_1} \quad (38)$$

The expression for the displacement of the double-walled carbon nanotubes as a function of the time passed is given as,

$$\varepsilon_1\left(t\right)=\sum_{j=0}^{N}\varepsilon_{1[j]}t^j \quad (39)$$

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$$\varepsilon_2(t) = \sum_{j=0}^{N} \varepsilon_{2[j]} t^j \quad (40)$$

Taking only the first 5 iterations, we have,

$$\varepsilon_1(t) = \varepsilon_{1[0]} + \varepsilon_{1[1]}t + \varepsilon_{1[2]}t^2 + \varepsilon_{1[3]}t^3 + \varepsilon_{1[4]}t^4 + \varepsilon_{1[6]}t^6 \quad (41)$$

$$\varepsilon_2(t) = \varepsilon_{2[0]} + \varepsilon_{2[1]}t + \varepsilon_{2[2]}t^2 + \varepsilon_{2[3]}t^3 + \varepsilon_{2[4]}t^4 + \varepsilon_{2[6]}t^6 \quad (42)$$

Substituting the value of each iteration into Eq. (41) and (42)

$$\varepsilon_1(t) = \Omega_1 - \left(\frac{K_1\Omega_1 + J_1\Omega_2}{2M_1}\right)t^2 + \frac{M_2K_1(K_1\Omega_1 + J_1\Omega_2) + M_1J_1(K_2\Omega_2 + J_2\Omega_1)}{24M_1^2M_2}t^4 + \frac{\dfrac{J_1\left(-\dfrac{J_2(J_1\Omega_2 + K_1\Omega_1)}{2M_1} - \dfrac{K_2(J_2\Omega_1 + K_2\Omega_2)}{2M_2}\right)}{12M_2} + \dfrac{K_1\left(-\dfrac{J_1(J_2\Omega_1 + K_2\Omega_2)}{2M_2} - \dfrac{K_1(J_1\Omega_2 + K_1\Omega_1)}{2M_1}\right)}{12M_1}}{30M_1}t^6 \quad (43)$$

$$\varepsilon_2(t) = \Omega_2 - \left(\frac{K_2\Omega_2 + J_2\Omega_1}{2M_2}\right)t^2 + \frac{M_1K_2(K_2\Omega_2 + J_2\Omega_1) + M_2J_2(K_1\Omega_1 + J_1\Omega_2)}{24M_2^2M_1}t^4 + \frac{\dfrac{J_2\left(-\dfrac{J_1(J_2\Omega_1 + K_2\Omega_2)}{2M_2} - \dfrac{K_1(J_1\Omega_2 + K_1\Omega_1)}{2M_1}\right)}{12M_1} + \dfrac{K_2\left(-\dfrac{J_2(J_1\Omega_2 + K_1\Omega_1)}{2M_1} - \dfrac{K_2(J_2\Omega_1 + K_2\Omega_2)}{2M_2}\right)}{12M_2}}{30M_2}t^6 \quad (44)$$

Applying Cosine After Treatment (CAT) technique

The Cosine After Treatment (CAT) technique is then introduced and applied to Eq. (43) and (44). This is done in order to produce new equations whose results would converge and enable proper analysis to be carried out [26-29]. The equations are.

$$\varphi_1(t) = \lambda_{1[1]}\cos(\upsilon_{1[1]}t) + \lambda_{1[2]}\cos(\upsilon_{1[2]}t) \quad (45)$$

$$\varphi_2(t) = \lambda_{2[1]}\cos(\upsilon_{2[1]}t) + \lambda_{2[2]}\cos(\upsilon_{2[2]}t) \quad (46)$$

Hence, the deflection of the carbon nanotube, ω , becomes,

$$\omega_1(x,t) = \varphi_1(t)\cdot\phi(x) \quad (47)$$

For the inner tube, and,

$$\omega_2(x,t) = \varphi_2(t)\cdot\phi(x) \quad (48)$$

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For the outer tube.

Where $\phi(x)$ is the boundary condition.

For simply supported boundary condition,

$$\phi(x)=\sin(\frac{n\pi x}{L}) \quad (49)$$

But L=1 (because of non-dimensionalizing). Hence,

$$\phi(x)=\sin(n\pi x) \quad (50)$$

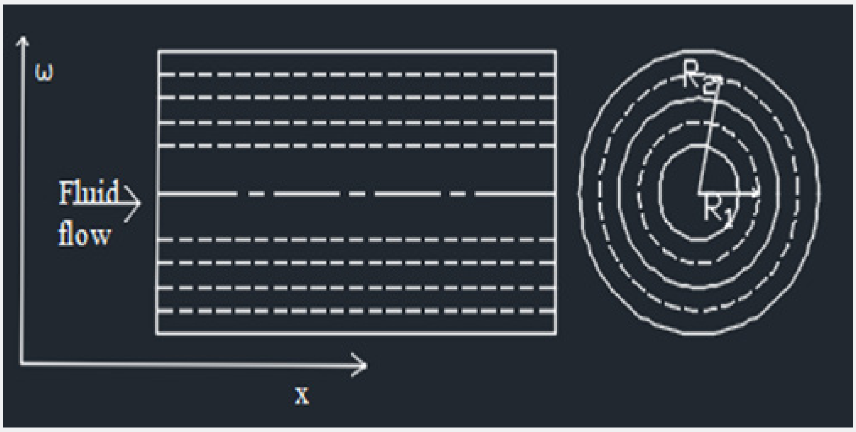

Figure 1: Simple representation of the DWCNT.

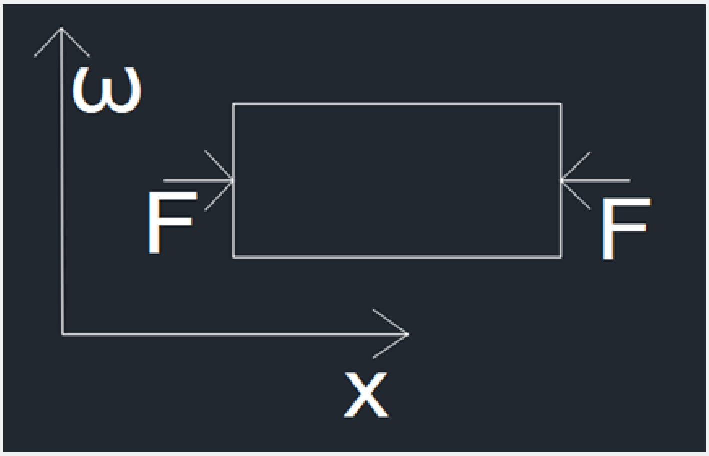

Figure 2: Representation of a beam under compressive axial load.

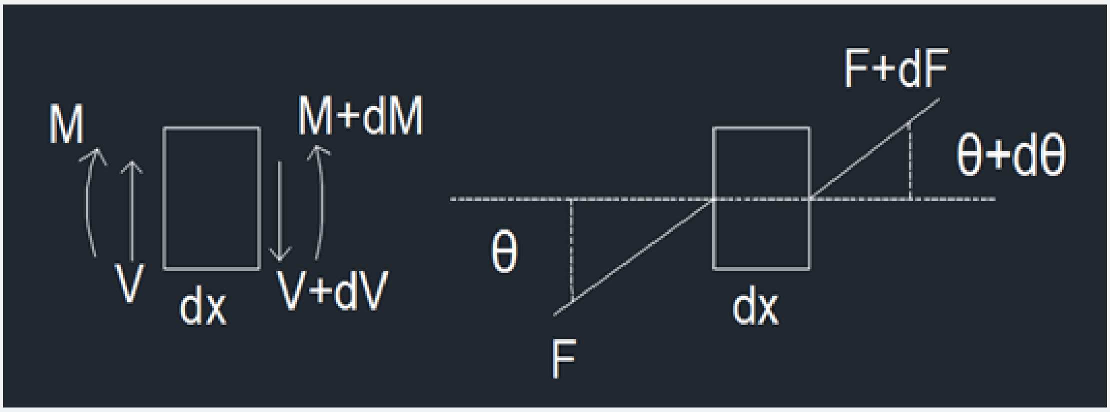

Figure 3: Diagrams of differential element of the beam.

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Results and Discussion

Dynamic Response Analysis

(Figures 4-7) show graphs representing the dynamic response of the double-walled carbon nanotube at different mode values. (Figure 4) shows how the deflection of the inner tube, at mode 1 varies with time. (Figure 5) shows the deflection of the inner tube at mode 2. (Figure 6) shows that of the outer tube at mode 1 while (Figure 7) is that of the outer tube at mode 2. The plots show that there is a significant increase in frequency of the vibration of the tubes as the mode number is increased, though the amplitude decreases [30].

Steady-state Analysis

(Figures 8-11) show the deflection of the double-walled carbon nanotube along the length of the tube. (Figure 8) shows the deflection of the inner tube plotted against points on the length of the nanotube. (Figure 9) shows that of the inner tube at mode 2. (Figure 10) shows the deflection of the outer tube along the length of the tube at mode 1 while (Figure 11) shows that for mode 2. The plots show that as the mode number increases, the number of deflections along the length also increases [31-33].

Conclusion

Based on the results and graphs obtained and displayed, it is therefore concluded that the modal number is a factor which greatly affects the dynamic response of the double-walled carbon nanotube, seeing as the amplitude of mode 2 is much smaller than those of mode 1. This means simply changing the modal number will cause such a large change in the vibration motion of the double-walled carbon nanotube. This is true for both the inner tube and outer tube. The inner tube also vibrates more than the outer tube.

Also looking at the steady-state analysis, the inner and outer tubes responded to it and behaved quite differently from one another. An increase in the modal number had a notable effect, adding an extra deflection of the tube. Another difference in behaviour is seen between the inner and outer tubes, with the inner tube displaying deflection in opposite direction to that of the outer tube. This is important to note that different measures or a combination of measures could be required to handle and control it.

Some other analyses can be carried out such as the stability analysis for instance. Having many more analyses results would help to give a better picture of the behaviour of the double-walled CNT. Also, analysis should be done for many other boundary conditions for the double-walled CNT in future works. This would help with the observation of the behaviour under the different conditions and can also serve as a comparison to select the most favourable condition under which the double-walled CNT should operate.

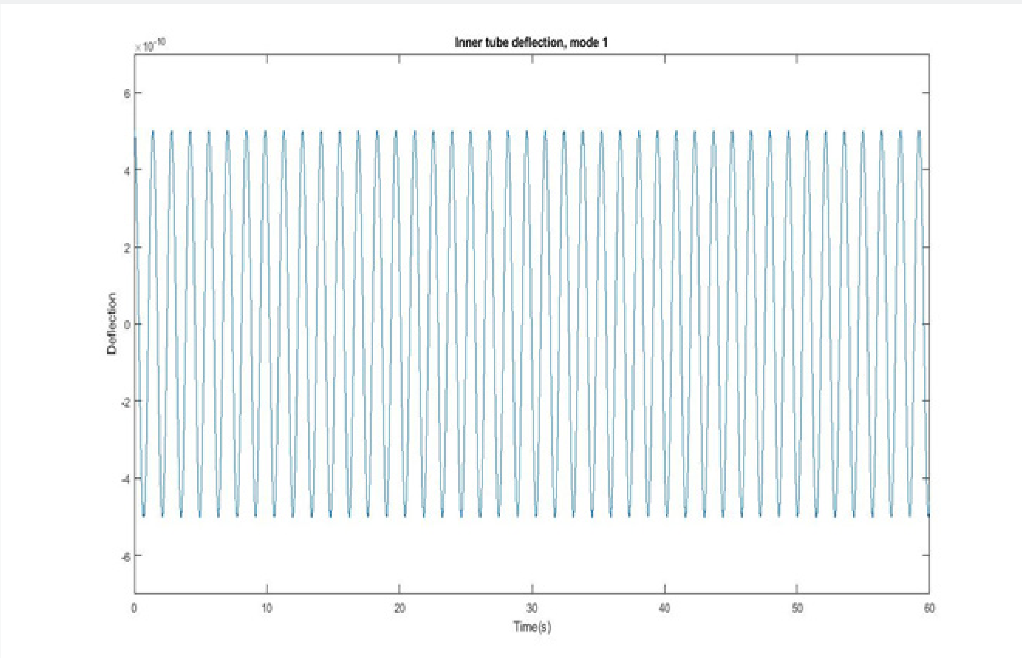

Figure 4: Dynamic response of the inner tube at mode 1(n=1).

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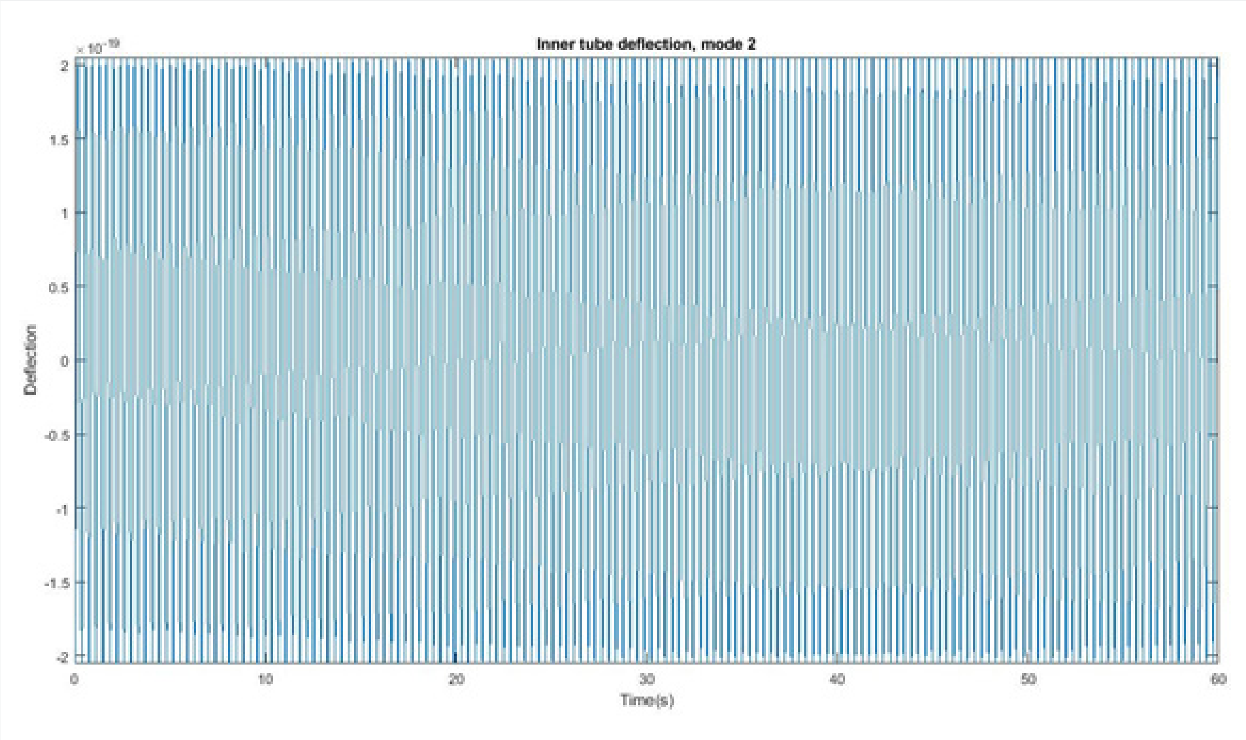

Figure 5: Dynamic response of the inner tube at mode 2(n=2).

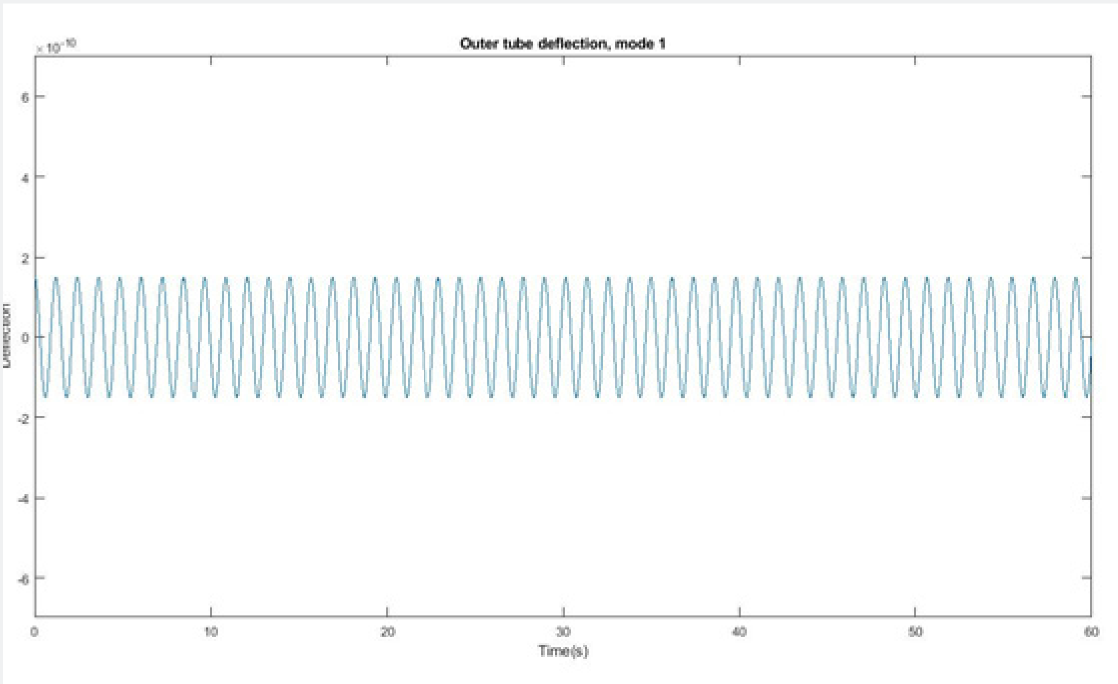

Figure 6: Dynamic response of the outer tube at mode 1(n=1).

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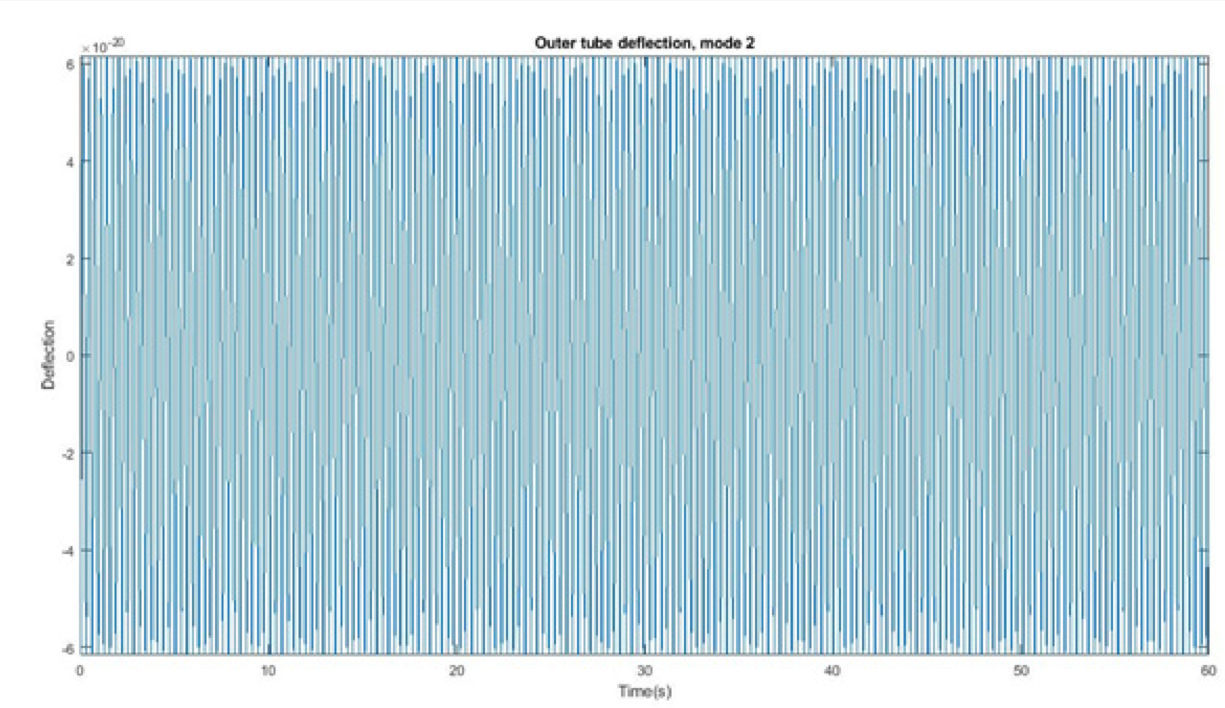

Figure 7: response of the outer tube at mode 2(n=2).

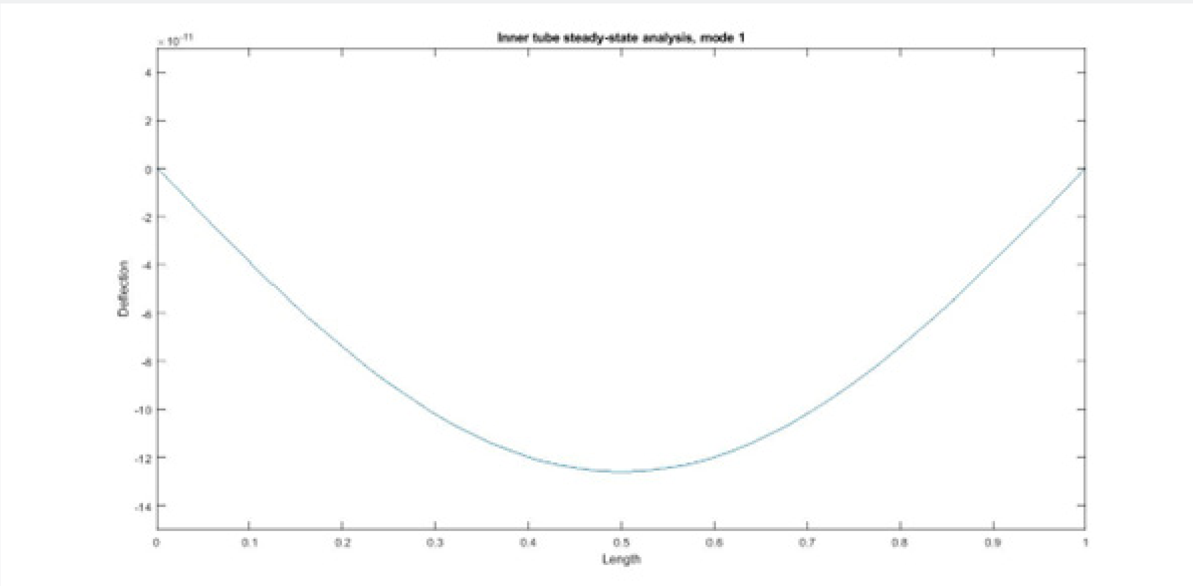

Figure 8 : Steady-state analysis of the inner tube at mode 1(n=1).

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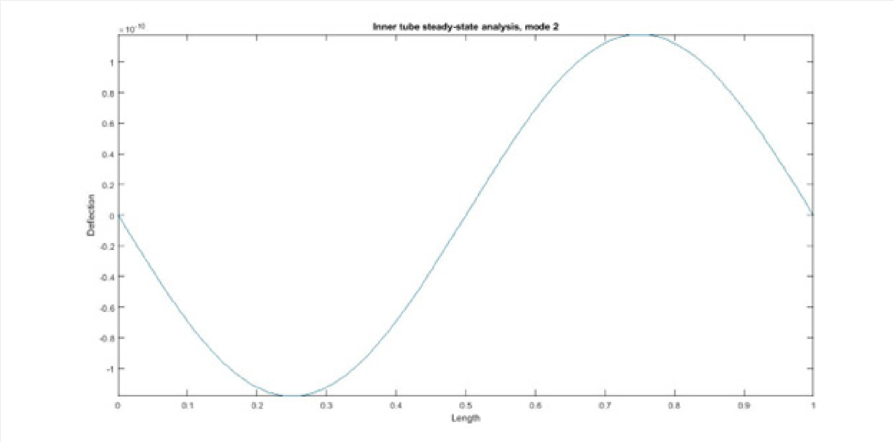

Figure 9: Steady-state analysis of the inner tube at mode 2(n=2).

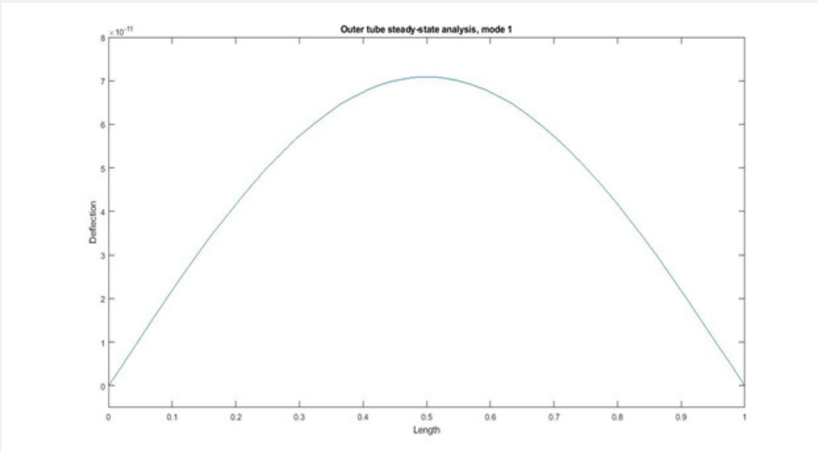

Figure 10: Steady-state analysis of the outer tube at mode 1(n=1).

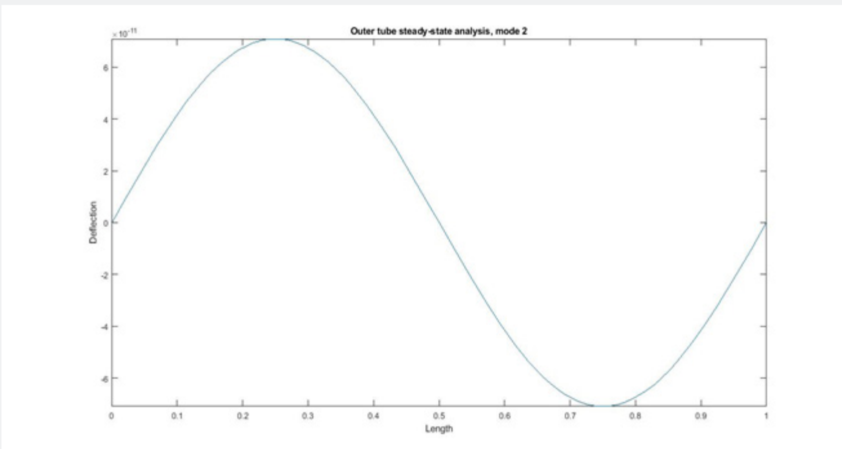

Figure 11: Steady-state analysis of the outer tube at mode 2(n=2).

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