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Modelling the nonlinear behaviour of double walled carbon nanotube based resonator with curvature factors

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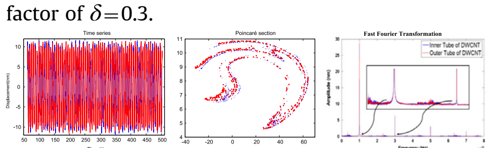
HIGHLIGHTS

- Nonlinear vibration analysis of a DWCNT with curvature factor is performed.
- Analysis is done using time response, Poincaré maps and FFT diagrams.
- Periodic, sub-harmonic and chaotic behavior are clearly seen.

GRAPHICAL ABSTRACT

Dynamic behaviour of DWCNT in context of time response, Poincaré section and Fast Fourier Transformation diagrams for a length of 20 nm, subjected to a mass of 1×10^{-7} femtograms and a curvature factor of $\delta = 0.3$.



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ABSTRACT

This paper deals with the nonlinear vibration analysis of a double walled carbon nanotube based mass sensor with curvature factor or waviness, which is doubly clamped at a source and a drain. Nonlinear vibrational behaviour of a double-walled carbon nanotube excited harmonically near its primary resonance is considered. The double walled carbon nanotube is harmonically excited by the addition of an excitation force. The modelling involves stretching of the mid plane and damping as per phenomenon. The equation of motion involves four nonlinear terms for inner and outer tubes of DWCNT due to the curved geometry and the stretching of the central plane due to the boundary conditions. The vibrational behaviour of the double walled carbon nanotube with different surface deviations along its axis is analyzed in the context of the time response, Poincaré maps and Fast Fourier Transformation diagrams. The appearance of instability and chaos in the dynamic response is observed as the curvature factor on double walled carbon nanotube is changed. The phenomenon of Periodic doubling and intermittency are observed as the pathway to chaos. The regions of periodic, sub-harmonic and chaotic behaviour are clearly seen to be dependent on added mass and the curvature factors in the double walled carbon nanotube. Poincaré maps and frequency spectra are used to explicate and to demonstrate the miscellany of the system behaviour. With the increase in the curvature factor system excitations increases and results in an increase of the vibration amplitude with reduction in excitation frequency.

1. Introduction

Since the innovation of carbon nanotubes (CNTs) by Iijima [1], these novel materials have attracted incredible attention from research communities. In the last few years, carbon nanotubes (CNTs) and double walled carbon nanotube discovered by Iijima [1], have concerned worldwide attention in the fields of chemistry, physics, diverse engineering, materials science, reinforced composite structures and mass sensors. Aydogdu and Ece [2] studied the buckling of in-plane loaded double-walled CNTs. It has been observed that sensors based on frequency shift offer a great deal of potential of reuniting the high-performance requirement of many sensing applications, including metal deposition monitors, chemical reaction monitors, biomedical sensors, mass detector, etc.

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[3–6]. This frequency shift principle has been used by many researchers in quantifying the variable which needs to be measure at frequent intervals.

CNTs can undergo large nonlinear deformations or even buckling [7] without permanent damage to the atomic structure and have demonstrated extraordinarily high thermal conductivity [8]. This allows many impending functions which includes thermal management, large nonlinear deflections in nanotube supported structures and resonant sensors with molecular level mass sensitivity. Very high frequency (VHF) nano electromechanical systems (NEMS) offer unparalleled sensitivity for inertial mass sensing [9]. It has been demonstrated that the best mass resolution using SWCNT corresponds to 30 xenon atoms.

Yan et al. [10] predicted the nonlinear vibration behaviour of a DWCNT based on the Donnell's cylindrical shell model. A similar problem was analyzed by Ke et al. [11] using nonlocal Timoshenko beam theory. Wu et al. [12] have reported the experimental consciousness of a CNT mass sensor and investigated the potential of multiwall carbon nanotubes (MWNTs) to be used as a mass sensor. One of the advantages in using carbon nanotube as mass sensor lies in the fact that they can be used for selective detection of chiral molecules. It has been reported by Vardanega et al. [13].

Sohlberg et al. [14] investigated the free vibrational behaviour of carbon nanotubes (CNT) while considering it as a solid slender beam. Blevins [15] applied the Euler–Bernoulli beam theory and derived corresponding Eigen values of the CNT free vibration. Mahan [16] proposed an elasticity solution of thin-walled cylinder for vibration analysis. It is noted that the atomistic approaches are more reliable than the continuum-based methods as a consequence of implementing interactions at the atomic scale [17–19]. Li and Chou [20] developed an equivalent structural beam to mimic interatomic forces of the covalently bonded carbon atoms. Later, Tserpes and Papanikos [21] presented the atomistic finite element (FE) model of single-walled carbon nanotubes (SWCNT) based on the Li and Chou equivalent structural beam concept.

In this paper authors have used continuum mechanics model to simulate the dynamic behaviour of double-walled carbon nanotubes. The utilization of the continuum approach is computationally less involved than the molecular approach. Continuum models are considered important in studying nano-vibration where it is proved to be difficult to measure physical parameters. The utilization of elastic continuum theories has been gaining more momentum over the earlier few years. In a series of papers, Zhang et al. [22–24] utilized a nonlocal double elastic beam model for studying the free transverse vibrations of double-walled carbon nanotubes, considering the effects of a small length scale, a compressive axial load, and a temperature change. Yoon et al. [25] reported the resonant frequencies and associated vibrational modes of an individual MWCNT embedded in an elastic medium. The free vibrations of double-walled carbon nanotubes (DWCNTs) modelled as elastic beams due to different boundary conditions between inner and outer tubes derived by Xu et al. [26]. Zhang and Shen [27] considered the buckling behaviour of single walled carbon nanotubes (SWCNTs) under combined axial compression and torsion by using molecular dynamics simulations. The global dynamics of the carbon nanotube when it acts as first-mode resonator has been investigated, with a focus on the chaotic behaviour [28].

Dynamic behaviour of triple-walled and multi-walled CNTs with considering the vdW forces between any two tubes was derived by Yan et al. [29,30]. Xu et al. [31] proposed a model for the nonlinear interlayer vdW force and performed the free vibration analysis of a DWCNT modelled as a beam. Nonlinear vibration of a DWCNT under harmonic excitation considering the nonlinear vdW force was developed by Hawwa et al. [32]. He et al. [33] suggested a nonlinear vdW force model for buckling and post-buckling analysis of MWCNTs modelled by a nested system of cylindrical shells. Joshi et al. [34] reported that SWCNT based sensors exhibit super-harmonic and sub-harmonic response with different level of mass.

Patel and Joshi [35,36] analyzed vibrational characteristics of double walled carbon nanotube (DWCNT) modelled using spring elements and lumped masses. The inner and outer walls of carbon nanotube were modelled as two individual elastic beams connecting each other by van der Waals forces. Also explores double walled carbon nanotubes as the sensing devices for biological objects including viruses and bacteria. Patel and Joshi [37–39] have been investigated resonant frequency of double walled carbon nanotubes with deviations along it is axis and different boundary conditions namely cantilever and bridged. The sensitivity of the apparently deviated double walled carbon nanotubes, different masses attached to the end of outer tube tip on DWCNT and centre outer tube tip of the bridged DWCNT and different lengths has been explored and presented. DWCNTs subjected to different boundary conditions and when used as mass sensing devices. The variation of such atomic vacancies in outer wall of Zigzag and Armchair DWCNT is performed along the length and the change in response is noted.

Fig. 1, (images taken by transmission electron microscopes at Institute Instrumentation Centre, Indian Institute of Technology, Roorkee) shows that these very small configurations are not usually straight, but rather have certain degree of curvature factor or waviness along the double walled carbon nanotube length. The curved morphology is due to process-induced waviness during manufacturing processes, in addition to mechanical properties such as low bending stiffness and large aspect ratio [38].

This paper deals with the nonlinear vibration response of a wavy double walled carbon nanotube based mass sensor. The double walled carbon nanotube is modelled as a doubly clamped elastic beam and subjected to an excitation in the form of an attached mass. The waviness of the double walled carbon nanotube is modelled as a sinusoidal curvature (along the length) with a small rise function. Due to the fixed end conditions during the vibration at primary resonance, stretching of the central plane is assumed to occur. A single-mode Galerkin approximation is used to derive a second order governing differential equation. This equation involves two nonlinear terms due to the geometry and the stretching of the central plane. The dynamics of the carbon nanotube mass sensor is investigated when it acts as first-mode resonator with a focus on the chaotic behaviour.

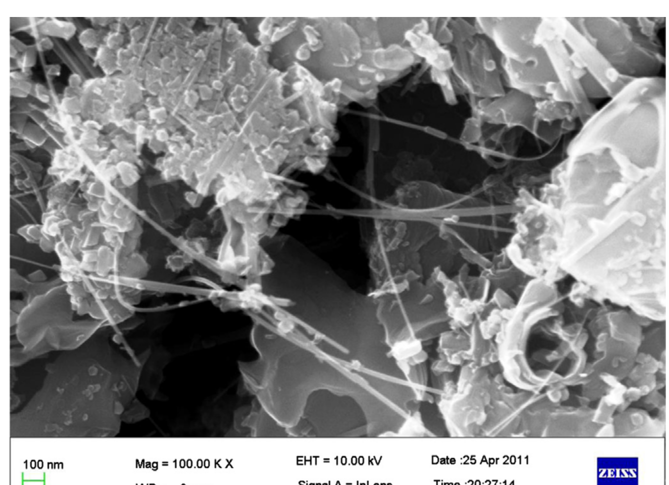

Fig. 1. Transmission electron microscope images of carbon nanotube indicating the waviness [38].