Measurement 73 (2015) 127–136

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Application of electrostatically actuated carbon nanotubes in nanofluidic and bio-nanofluidic sensors and actuators

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ARTICLE INFO

Article history:
Received 4 May 2014
Received in revised form 12 April 2015
Accepted 6 May 2015
Available online 21 May 2015

Keywords:
Carbon nanotubes
Nonlocal elasticity theory
Nanosensors and nanoactuators
Nanofluidics
Bio-nanotechnology

ABSTRACT

The paper investigates the effects of fluid flow on the static and dynamic behaviors of electrostatically actuated carbon nanotubes using nonlocal elasticity theory. The influences of various parameters of fluid flow including fluid viscosity, velocity, mass and temperature on the mechanical behaviors of the carbon nanotubes under static and step DC voltages are studied using this theory. The results computed from the nonlocal elasticity theory are compared with those estimated using the classical elasticity theorem and the outcomes demonstrate the applicability of the electrostatically actuated carbon nanotubes as nano sensors and nano actuators in nanofluidic systems. The nanosystem can be potentially applied in precise nanoscale drug delivery as well as other bio-nanofluidic processes.
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1. Introduction

Fluid flow through the nano pipes and nano channels can possess various applications in nanotechnology ranging from nano medicine to nano engineering [1–3]. Carbon nanotubes (CNTs) are excellent options for these purposes due to their extraordinary mechanical properties, chemical and thermal stability, and hollow geometries. For example, they can be served as hydraulic fluids in support platforms or carry reactant molecules into reaction chambers [4]. Furthermore, the CNTs have potential usage as cancer therapy devices or nano-vessels for conveying and storing fluids and drug delivery in bio-nanotechnology [5]. As an example, nano pipes that act like tiny straws deliver medicines to a person's bloodstream or to a highly specific location in the body.

According to the potential applications of the CNTs conveying fluid, it is obvious that the effects of fluid flow on the mechanical behaviors of the CNTs should be scrutinized. Of course, the mechanical behaviors of the CNTs conveying fluid were studied before. But, applying electrostatic actuation to the nanosystem for the reasons described in the following paragraphs and studying the effects of nonlocality on its behavior has not been investigated yet. Yoon et al. maybe was the first ones studied the flutter instability of the CNTs resulted from the fluid flow [6]. They presented the natural frequencies and damping of the CNT for various fluid velocities. Their work had some shortages that were compensated by Wang and Ni [7]. They comprehensively investigated the mentioned phenomena. In another research, they studied the effects of viscosity on the instability of the CNTs conveying fluid flow [8]. The authors of [7,8] applied the well-known Euler–Bernoulli beam model in their researches but Chang and Lee used the Timoshenko beam model considering the rotational inertia and shear deformation to investigate the effects of internal fluid flow on the transverse vibration [9]. They reported the natural frequencies of the system for different aspect ratios.

Despite some studies regarding the effects of fluid flow on the static and dynamic behaviors of the CNTs that some

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http://dx.doi.org/10.1016/j.measurement.2015.05.009
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of them reviewed above, controlling the flow was not investigated in detail. Only some limited number of papers mentioned it very basically through reporting the rudimentary conceptual designs of the CNTs as nano valves [10–12]. It is clear that every fluidic system and piping should have effective and applicable controlling devices such as valves, flow meters, pressure sensors, viscometer, and densitometer. The nano fluidic systems in general and bio-nanofluidic systems in particular are not definitely exceptions of this fact. The development of such systems for the fluid flow through the nanotubes is exactly one of the main goals of this research.

In spite of invaluable ideas behind the designs presented in [10–12], they may not have reliable performance in the real systems especially in those requiring very fast actuation and response due to their extremely slow responses. This paper tries to develop a more applicable technique to apply the CNTs as the nano valves as well as some other fluid controlling devices such as viscometer, densitometer and velocity sensor. The electrostatic actuation of the CNTs conveying fluid can help the mentioned roles. In electrostatic actuation, two conductive electrodes parted from each other with an initial gap are applied an electrical potential difference. In general, one of the electrodes is fixed and the other one is movable (Fig. 1).

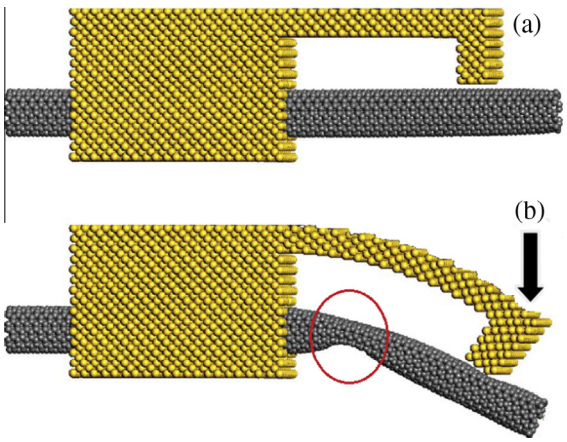

Fig. 1. Electrostatic actuation of a CNT conveying fluid.

Positive and negative charge distributions on the electrodes resulted from the applied potential difference leads to attract the movable electrode towards the fixed one.

This deflection is similar to the deflection shown in Fig. 2. As shown in Fig. 2, by applying an external transverse force to a constrained CNT conveying fluid, a critical section deforms so that it does not allow the fluid flow to pass or can confine it [11,13]. The level of confinement is a function of the applied force and the resultant deformation. When the applied voltage reaches to a threshold value, the CNT does not endure the attractive force resulted from the electrostatic actuation and interatomic interactions anymore and suddenly drops on the fixed electrode. In the discussed instability, the local buckling of the CNT displayed in Fig. 2 can be so that it can confine the fluid stream completely. This concept is applied for nano valve application of the CNTs. Obviously, the fluid flow affects the mechanical properties of the CNTs and consequently the pull-in voltage is a function of the fluid parameters. Thus, it can be applied as a nanofluidic sensor and can sense the various fluid parameters via sensing the alteration in the instability voltage.

In this paper, we are going to investigate the applicability of the proposal suggested in the above lines using the nonlocal theory (NLET) proposed by Eringen and Edelen [14]. According to this theory the stress at a reference point x in an elastic body not only is a function of the strain at the point but also relates to the strains at every point of the body [15]. The NLET is applied due to failing or less accuracy of the classical elasticity theories (CETs) in predicting the mechanical behaviors of the micro and nano structures [16,17]. Numerical solution techniques are always helpful in analyzing the governing complex equations [18,19] and are going to be applied in this paper.

2. System description

As shown in Fig. 1, suppose that a CNT is suspended over some graphene sheets with an initial gap equaling G_0 (state 1 in the figure). The CNT as the positive electrode and graphene sheets as the negative electrode (ground plate) are applied an electrical potential difference (V). The positive and negative charge distributions over the electrodes make an attractive force between them. This

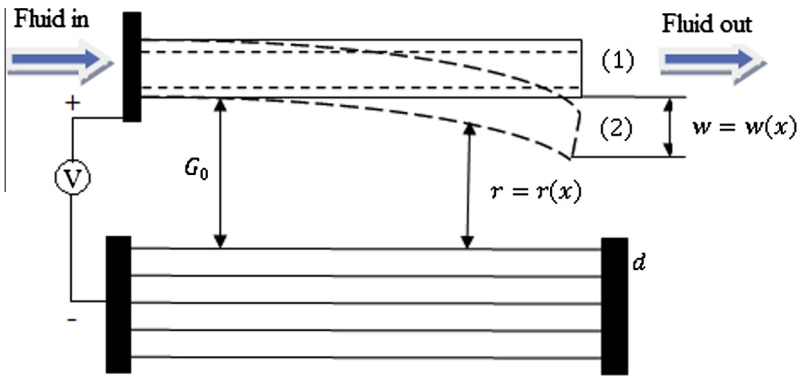

Fig. 2. Local buckling of a CNT under external transverse force.

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