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Size-dependent nonlinear vibration analysis of carbon nanotubes conveying multiphase flow

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ABSTRACT

An understanding of the dynamic behavior of the carbon nanotubes (CNTs) conveying fluid is very important for exploring the applications in nanoscale systems. Due to the molecular network disruption, the passing flow has multiphase nature. In this regard, the nonlinear vibration behavior of the CNT conveying multiphase flow is investigated by considering the small scale effects based on the nonlocal theory. The effect of the multiphase flow on the CNT's vibration behavior is modeled by the resultant random uncertainty in the external excitation along with considering the slip flow velocity profile. After extraction of the governing equation by implementing Hamilton's principle and discretizing it by the Galerkin method, the resulting equations are solved numerically. Due to the stochastic nature of the differential equations, the statistical parameters of the response have been obtained by Monte–Carlo simulation. By studying the deflection of the midpoint of the CNT and also considering corresponding upper and lower limit band (confidence interval), extended results of uncertainty effects have been obtained. Moreover the effect of nonlocal parameter, flow velocity and Knudsen number on the statistical dynamic behavior of the system have been investigated. The results show that as the molecular behavior of the flow increases the uncertainty in the system and the confidence interval increase.

1. Introduction

The extraordinary properties of carbon nanotubes (CNTs) enable a variety of applications such as storing and conveying fluids in nanoscale and capsules for drug delivery. In this regard, a large number of studies have been done to investigate the dynamic behavior of CNTs conveying fluid. The classic beam theory can be used to predict the key parameters of the vibration behavior [1]. However, to obtain realistic results and consider the small scale effects, nonlocal elasticity theory is more reliable [2–4]. Nonlocal elasticity theory considers the scale effects by assuming the stress at a point to be a function of strain field at every other points in the body. Fakhrabadi et al. [5] applied the classical and nonlocal elasticity to study the deflection and instability of electrostatically actuated CNTs. They obtained more accurate results based on the non-classical elasticity theory. Cigeroglu and Samandari [6] investigated the nonlinear free vibration of curved double-walled carbon nanotubes embedded in an elastic medium. They utilized differential quadrature method (DQM) to obtain the dynamic response of the CNT and showed that as the nonlinear resonance frequency increases the vibration amplitude rises. Kiani [7] investigated the free transverse vibration of an elastically supported double-walled CNT embedded in an elastic medium under initial axial force. He used nonlocal shear deformable beam theory to model the carbon nanotube. The obtained results showed that by increasing the lateral and rotational stiffness of the surrounding foundation the predicted first dimensionless frequency of the system increases. In another investigation, Kiani [8] studied the free dynamic deflection of an elastically supported double-walled carbon nanotube subjected to a longitudinally varying magnetic field by implementing the nonlocal Rayleigh, Timoshenko, and higher-order beam theories. The results revealed that the effect of the small scale parameter on the frequencies of higher vibration modes is more obvious.

On the other hand, molecularly smooth inner surface of CNT gives rise to the speed of flowing fluid by orders of magnitude faster than through other pores of similar size [9]. In this condition, the fluid is no longer continuous and has discontinuities in both density and energy properties. Experimental evidence of slip has been demonstrated in study of drainage experiments by Baudry et al. [10]. Mirramezani and Mirdamadi [11] used slip flow velocity to correct the fluid velocity profile and showed that the molecular behavior of the flow causes sooner divergence instability of the CNT. Rashidi et al. [12] showed that incorporating the nanoscale effects on the fluid properties changes the critical velocities considerably. In another study, Kaviani and Mirdamadi [13] investigated the effect of slip boundary condition on the viscosity of a nano-flow passing through a CNT. The obtained results showed that taking into account the nanoscale effect on the flow,

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changes the fluid viscosity drastically. Arani et al. [14] studied the vibration of embedded double-walled carbon nanotube (DWCNT) conveying fluid under uniform magnetic field with slip conditions based on nonlocal elasticity theory. They concluded that considering slip boundary conditions results in sooner stability of DWCNTs. In addition, fluid molecules, particularly water, in confinement exhibit several phase transitions as their network of hydrogen bonds is disrupted, consequently the flow passing through the CNT has a multiphase character [15]. Sasic et al. [16] showed that the dynamic behavior of systems in the field of multiphase flow beds may be studied by using the experimental flow pressure fluctuation signals exerted on the bed's wall. They showed that these fluctuations can be assumed as irregular narrow band noise signals. The multiphase flow bed's dynamic behavior might also be considered as a chaotic problem and as a result some studies have been done on the chaotic behavior of tubes conveying multiphase flow [17–19]. From nonlinear vibration aspect, modeling of a CNT conveying multiphase flow is a challenging task and the vibration of a tube conveying multiphase flow is inevitably affected by some randomly uncertain factors, therefore the result predicted by the deterministic dynamic theory will deviate from the real one [20]. The randomly uncertain factors due to the multiphase flow can be modeled as randomness in the external excitation. The excitations exerted on the bed's wall could be the result of the pulsating flow, inside and outside temperature or pressure fluctuations.

In this investigation, the statistical nonlinear nonlocal vibration of CNT conveying multiphase flow is studied. In addition to incorporating the small scale effects on the solid structure via nonlocal theory, the influence of nanoscale on the fluid flow is also counted in. As discussed above, one of the consequences of nanoscale flow is the multiphase character of the passing fluid through the CNT. In this research, by considering the outcome of the multiphase flow on the vibration behavior of the CNT, the uncertainties due to the phase transition in the flow and pressure fluctuations is modeled. To this end, the slip boundary condition in the flow is considered and the narrow band noise is added to the periodic excitation of the system as well. In this regard, the equation of motion is derived by implementing Hamilton's principle and after discretizing the governing equation, large number of dynamic response samples are obtained numerically, then Monte–Carlo simulation is used to derive the mean response and the confidence interval. Finally, the effect of system parameters on the statistical dynamic behavior of the system has been investigated.

2. Multiphase flow in nanotubes

Discontinuities and molecular behavior of fluids, and phase transitions due to molecular network disruption cause a great deviation from the continuum mechanics laws [11,15]. Todd et al. [21] made a comparison between the results obtained from Navier–Stokes hydrodynamics and molecular simulation. Due to the molecular behavior, the results revealed that the velocity profiles associated with each method are different. Here, in order to take into account the molecular behavior of the multiphase flow in the nanoscale, slip flow velocity is derived and the uncertainty due to the multiphase flow is modeled as randomness in the external excitation.

2.1. Flow regime criterion

To evaluate the validity of the continuum mechanics or molecular models, one needs a measure to know the flow regime, i.e. identify the continuum and molecular flow. For gas and liquid flows, the measures are different which are described in the following.

In the case of gases, the ratio of the mean free path to the characteristic dimension of the gas is known as the Knudsen number, Kn, the value of which is used as a criterion to know the flow regime. A very small Kn, ($Kn < 0.001$) describes a system that is well within the continuum laws, $0.1 < Kn < 10$ describes transition flow regime and $10 < Kn < 100$ describes free molecular flow regime [22].

In the case of liquids, Loose and Hess [23] showed that the molecular behavior becomes more dominant as the strain rate, $\dot{\gamma}$, exceeds twice the molecular frequency scale, i.e.

$$\dot{\gamma} = \frac{\partial u_x}{\partial r} \geq 2f \tag{1}$$

where u_x and r are the axial velocity of the fluid inside the CNT and the radial distance from the center of the CNT, respectively. f is the molecular frequency scale that depends on the type of the fluid and its molecular collision radius. However, in order to use the criterion of the gas flow to know the regime of the liquid flow, one may use the Kn number (i.e. using Kn instead of Eq. (1)). Since, the mean free path in liquids is much less than in gases, Kn for liquids is less than that for gases as mentioned above [24].

2.2. Slip boundary condition flow velocity

Once the measure to distinguish the molecular behavior of the flow is described, the velocity profile can be obtained. Based on the Navier–Stokes equation, the velocity profile for a laminar flow in a tube is [25]:

$$u_x = \frac{1}{4\mu}\frac{\partial P}{\partial \widehat{x}} r^2 + c_1 \ln r + c_2 \tag{2}$$

where $\widehat{x}$ is the coordinate along the CNT, μ is fluid viscosity, and $\partial P/\partial \widehat{x}$ shows the pressure gradient. The boundary condition at the center of the CNT enforces $c_1 = 0$. Nguyen and Wereley [26] suggested the following equation as the slip boundary condition

$$u^*_{s-w} - u^*_w = L_s \frac{\partial u^*_s}{\partial r^*} \tag{3}$$

where u^*_{s-w} is the dimensionless axial velocity of the flow near the CNT wall, u^*_w is the dimensionless axial velocity of the wall, u^*_s is the dimensionless axial slip flow velocity, r^* is the dimensionless radial distance, and L_s is the ratio of the slip length to the characteristic dimension of the flow field, which is given by [26]

$$L_s = \frac{2 - \sigma_v}{\sigma_v}\left(\frac{Kn}{1 + Kn}\right) \tag{4}$$

where σ_v is the momentum accommodation coefficient, value of which depends on the type of the fluid and the surface quality of the tube, which is assumed to be 0.7 [12]. It can be seen from Eq. (4) that as the molecular behavior reduces, ($Kn \to 0$), L_s tends to zero, and slip boundary condition in Eq. (3) changes to the conventional no-slip boundary condition. Using Eqs. (2)–(4) and knowing that all the parameters in Eq. (3) have become dimensionless by dividing each of them to their average values, e.g. $u^*_s = u_s/\bar{u}_s$, one obtains

$$c_2 = -\frac{r_1^2}{4\mu}\frac{\partial P}{\partial \widehat{x}}\left(1 + \frac{4}{3}L_s\right) \tag{5}$$

where r_1 is the inner radius of the CNT. Therefore, the velocity profiles with no-slip and slip boundary conditions become respectively, as

$$u_{ns} = \frac{1}{4\mu}\frac{\partial P}{\partial \widehat{x}}\left(r^2 - r_1^2\right) \tag{6}$$

$$u_s = \frac{1}{4\mu_e}\frac{\partial P}{\partial \widehat{x}}\left(r^2 - r_1^2 - \frac{4}{3}L_s r_1^2\right) \tag{7}$$