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Size-dependent thermo-mechanical vibration and instability of conveying fluid functionally graded nanoshells based on Mindlin's strain gradient theory

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ABSTRACT

The free vibration and instability characteristics of nanoshells made of functionally graded materials (FGMs) with internal fluid flow in thermal environment are studied in this paper based upon the first-order shear deformation shell theory. In order to capture the size effects, Mindlin's strain gradient theory (SGT) is utilized. The mechanical and thermal properties of FG nanoshell are determined by the power-law relation of volume fractions. The Knudsen number is considered to analyze the slip boundary conditions between the flow and wall of nanoshell, and the average velocity correction parameter is used to obtain the modified flow velocity of nano-flow. The governing partial differential equations of motion and associated boundary conditions are derived by Hamilton's principle. An analytical solution method is also employed to solve the governing equations under the simply-supported end conditions. Then, some numerical examples are presented to investigate the effects of fluid velocity, longitudinal and circumferential mode numbers, length scale parameters, material properties, temperature difference and compressive axial loads on the natural frequencies, critical flow velocities and instability of system.

1. Introduction

Shells among the fundamental engineering structures have many industrial applications. Numerous investigations are carried out to study different aspects of behavior of shell-type structures, including free vibration [1], forced vibration [2], static and dynamic buckling [3], post-buckling [4], thermal buckling [5] and biomechanical properties [6]. Cylindrical, spherical and conical shells can be used to model pipes, reservoirs, tanks and many other conveying fluid structures. Works of Païdoussis and Denise [7], Weaver and Unny [8] and Matsuzaki and Fung [9] are the first outstanding studies in this field. Amabili and co-worker [10] analysed the free vibration characteristics of circular cylindrical thin shells. Vibration of anisotropic cylindrical shells with internal and external flowing fluid [11], partially or completely filled with liquid for axisymmetric and beam-like anisotropic cylindrical shells [12] are investigated by Lakis et al. Zhou studied the vibration and stability of conveying fluid ring-stiffened thin-walled cylindrical shells by applying Flugge shell theory [13].

Functionally graded materials are considered as a special case of composites in which the material properties are varies over the volume. Employing the ceramic and metal layers at two sides of FGM, leads to use the best mechanical properties of both materials and makes it a suitable candidate of many applications [14–18]. Huang and Han presented the buckling and post-buckling analysis of the FG cylindrical shells [19]. Effects of the thermal and mechanical loads on the post-buckling responses of a functionally graded plate are perused by Wu et al. [20]. Sheng and Wang discussed the nonlinear vibration responses of an FG cylindrical shell subjected to thermal and axial loads [21]. They considered the Von Kármán nonlinearities and used the multiple scales method to solve the equations analytically. They also analysed the vibration of conveying fluid FG cylindrical shells in thermal environment and embedded in an elastic medium [22].

It is well known that the classical theory of continuum mechanic cannot consider the small-scale size effects. In this regard, non-classical continuum mechanic theories are developed to capture the size effects. Among these theories, the nonlocal elasticity theory [23], Mindlin's strain gradient theory [24], couple stress theory [25], strain gradient theory [26], modified couple stress theory [27] and modified strain gradient theory [28] are the most popular and strong ones. Later, various researchers developed the nonclassical small-scale beam, plate and shell models

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incorporating the size effects to estimate the size-dependent static and dynamic mechanical characteristics of structures at nano- and micro-scales [29–42]. For instance, Ghorbanpour et al. [43] studied the nonlinear vibration and instability of conveying fluid double-walled boron nitride nanotubes (DWBNNTs) based on nonlocal shell theory. Zhou and Wang [44] used the modified couple stress theory to present the vibration characteristics of a conveying fluid micro-scale cylindrical shell with simply-supported end conditions. Ansari et al. [45] obtained the nonlinear vibration responses of single-walled boron nitride nanotubes (SWBNNTs) with internal flowing fluid based on modified strain gradient theory. Using the method of multiple time scales, Kural and Ozkaya [46] analytically investigated the size-dependent vibrations of a microbeam conveying fluid embedded on an elastic foundation based on the modified couple stress theory and Euler-Bernoulli beam model.

The above literature review shows that there are few papers which analysed the size-dependent behavior of conveying fluid micro/nano shell-structures with non-classical elasticity theories. So this work is assigned to present the free vibration and instability characteristics of conveying fluid FG nanoshell by employing Mindlin's strain gradient theory. To this aim, the properties of functionally graded material and flowing fluid model are introduced first. Then, the governing equations and related boundary conditions are obtained by applying Hamilton's principle. The Navier-type exact solution is used to solve the governing equations for both end simply-supported nanoshell. The effects of different parameters on the natural frequencies of conveying fluid FG nanoshell are examined in the case studies. Also, in order to validate this study, the results of special cases of present approach are compared with some works in the field.

2. Material properties of FG nanoshell

Fig. 1 shows a schematic view of a fluid-conveying circular cylindrical nanoshell with geometrical properties as uniform thickness h, midsurface radius R, and length L. A curvilinear coordinate system is chosen for the nanoshell. The origin of coordinate is located in the middle surface and the axial, circumferential and radial directions of a typical point are denoted by x, y and z, respectively. The nanoshell is made of functionally graded materials in which the inner surface of nanoshell ($z=-h/2$) is fully ceramic and the outer surface ($z=h/2$) is metal rich and consequently the material properties are vary continuously in thickness direction. Moreover, it is assumed that the variation of mechanical properties of FG nanoshell is based on the power-law distribution of the volume fractions. In this regard, the Young's modulus E, Poisson's ratio ϑ, mass density ρ and thermal expansion α are as follows through the FG nanoshell thickness

$$E(z)=\left(E_m-E_c\right)V_f(z)+E_c \tag{1a}$$

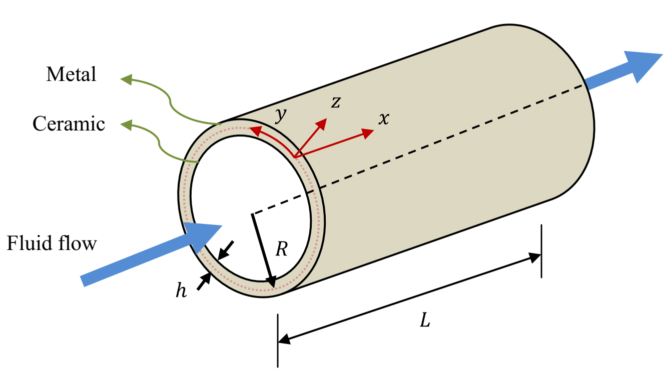

Fig. 1. Schematic of fluid-conveying FG nanoshell.

$$\vartheta(z)=\left(\vartheta_m-\vartheta_c\right)V_f(z)+\vartheta_c \tag{1b}$$

$$\rho(z)=(\rho_m-\rho_c)V_f(z)+\rho_c \tag{1c}$$

$$\alpha(z)=(\alpha_m-\alpha_c)V_f(z)+\alpha_c \tag{1d}$$

where the subscripts m and c stands for the metallic and ceramic constituents respectively, and the volume fraction V_f is defined as

$$V_f(z)=\left(\frac{1}{2}+\frac{z}{h}\right)^{\kappa} \tag{2}$$

in which κ signals the power-law index.

3. Governing equations of motion

With using the first-order shear deformation shell theory (FSDT), the dynamic displacement field for the circular cylindrical nanoshell shown in Fig. 1 can be written as

$$u_x=u(t,x,y)+z\psi_x(t,x,y),\ u_y=v(t,x,y)+z\psi_y(t,x,y),\ u_z=w(t,x,y) \tag{3}$$

in which t points time; u, v and w are displacement components of a point in the middle surface; ψ_x and ψ_y are the rotation of the middle surface normal about y and x axes, respectively.

3.1. Flow loading

To investigate the interaction forces of the fluid flow and nanoshell walls, it is assumed that the flowing fluid is incompressible, inviscid, isentropic and irrotational. It is reported [47] that the perturbation pressure applied on the wall of nanoshell is given by

$$P=F_{mn}\left(\frac{\partial}{\partial t}+U\frac{\partial}{\partial x}\right)^2 w \tag{4}$$

and

$$F_{mn}=\frac{\rho_f}{\alpha_m}\frac{I_n(\alpha_m R)}{I_n'(\alpha_m R)} \tag{5}$$

in which U shows the flow velocity in the axial direction; ρ_f is the fluid density; $\alpha_m=\frac{m\pi}{L}$ and m stands the number of axial half waves; I_n represents the modified Bessel function of the first kind of order n and I_n' is its derivative; also n denotes for the number of circumferential waves.

Furthermore it should be mentioned that in nano-scale, the continuum flow regime may not be valid any more [48]. With considering the Knudsen number K_n, one can model the slip boundary conditions between the nano-flow and walls of nanoshell properly. In this regard, the flow velocity can be expressed as [48, 49]

$$U=VCF\times U_{no-slip} \tag{6}$$

in which $U_{no-slip}$ denotes the flow velocity of no-slip boundary conditions and VCF is the average velocity correction factor as

$$VCF=\left(1+aK_n\right)\left(4\left(\frac{2-\sigma_v}{\sigma_v}\right)\left(\frac{K_n}{1+K_n}\right)+1\right) \tag{7}$$

where σ_v is assumed to be 0.7 and