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The size-dependent free vibration analysis of a rectangular Mindlin microplate coupled with fluid

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ABSTRACT

In this paper, the size-effect and fluid-structure interaction on the vibrational characteristics of a simply supported rectangular microplate is investigated. The influences of rotary inertia and transverse shear deformation which have the remarkable role in the analysis of moderately thick microplates are considered. The first order shear deformation theory along with the modified couple stress theory has been used to perform the free vibrational analysis of the considered problem. The Hamilton's principle is employed to derive the governing differential equations of motion and the corresponding boundary conditions. The fluid is assumed to be incompressible, inviscid and irrotational. The fluid velocity potential is obtained using the boundary and compatibility conditions. Then the Rayleigh-Ritz method has been applied to calculate the natural frequencies of the system. A convergence study is carried out. The obtained results are compared against available data in the published papers and very good agreements have been observed. Finally by referring to the numerical results, the effects of dimensionless thickness, side to thickness ratio, aspect ratio, material length scale parameter and fluid depth ratio on the natural frequencies are discussed in details.

1. Introduction

Nowadays, micron and submicron structures, for example micro-bars, micro-beams and micro-plates, are utilized in a lot of applications including several micro/nano-electro mechanical systems (MEMS and NEMS), such as micro-actuators (Chaterjee and Pohit, 2009), micro-switches (Samaali et al., 2011), micro-pumps (Laser and Santiago, 2004; Nisar et al., 2008) and atomic force microscopes (AFMs) (Rahaeifard et al., 2009). In addition, they have been used in different fields such as microbiology (Singh, 2009), radiology (Dilmanianet al, 2008) and biotechnology (Filippini et al., 2003).

Small scale, low potency usage and extraordinary mechanical properties are the main advantages of using these systems. So, there is a noteworthy interest among the researchers to study the mechanical behavior of such structures.

The size-dependent vibration behaviors and deformations in micron and submicron elements are experimentally observed (Fleck et al., 1994; McFarland and Colton, 2005; Stölken and Evans, 1998). These experiments have revealed a notable difference between the stiffness of materials in micro-scale and those of the free-scale that have been evaluated by the classical continuum mechanics theory. So, within the past years, the researchers have found that the size-dependent behavior is an intrinsic property of materials which will be appeared when the characteristic size (e.g. diameter, thickness) is close to the material length scale parameter. The length scale parameter of the materials can be obtained by experiments (Fleck et al., 1994; Stölken and Evans, 1998; Lam et al., 2003). Therefore, the classical deformation theories, which have no internal material length scale parameter, are unable to interpret the size-dependent behavior of micron and submicron systems. Accordingly, employing the higher-order elasticity theories is inevitable which are acceptably adequate to capture the size-dependency. For this purpose, some higher-order elasticity theories, such as strain gradient theory (Fleck and Hutchinson, 1993, 2001), nonlocal elasticity theory (Eringen, 1983) and couple stress theory (KOlTER, 1964; Mindlin and Tiersten, 1962; Toupin, 1962) have been developed during the past years.

The couple stress theory is a non-classical continuum theory proposed by Mindlin and Tiersten (1962), Toupin (1962) and Koiter (1964) in which the constitutive equations includes four material constants i.e. two Lame constants and two higher-order material length scale parameters. It is worth mentioning that determining the material length scale parameters by experiments require much computational cost and plenty of time. Thus, Yang et al. (2002) have proposed another higher-order equilibrium equation to govern the behavior of couples in

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addition to the conventional equilibrium relations of forces and moments. With this concept, they have deduced that the material length scale parameters reduced to one rather than two in classical couple stress theory. Their formulations are well-known as the modified couple stress theory.

Jomehzadeh et al. (2011) have utilized the Kirchhoff plate model along with the modified couple stress theory to investigate the dynamic analysis of circular and rectangular microplates. They have used the Levy's method to obtain the solution. The free vibration analysis of a Mindlin microplate based on the modified couple stress theory has been carried out by Ma et al. (2011) and Ke et al. (2012). Asghari and Taati (2013) have investigated the static and dynamic behavior of a functionally graded (FG) microplate based on the Kirchhoff theory along with the modified couple stress theory. Simsek et al. (2015) have used the Kirchhoff plate model and the modified couple stress theory to study the forced vibration analysis of a microplate that is subjected to a moving load. According to the numerical results, they have studied the influence of the material length scale parameter, aspect ratio, boundary conditions and the moving load velocity on the vibratory response of the microplate. Askari and Tahani (2015) have established the extended Kantorovich method (EKM) to obtain the free vibrational characteristics of the rectangular Kirchhoff microplates with clamped boundary conditions and based on the modified couple stress theory. Thai and Choi (2013) have studied the size-dependent models for bending, buckling and vibrations of the plate with simple boundary conditions. The plate is made of functionally graded material (FGM) and they have used the Kirchhoff and Mindlin assumptions to model the kinematics of the plate.

Li and Pan (2015) have developed a size-dependent model for static bending and free vibration of a functionally graded piezoelectric microplate. They have adopted the modified couple stress and the extended sinusoidal plate theories. Adopting the Kirchhoff plate theory in conjunction with the modified couple stress theory, (AkgÖz and Civalek, 2013) have investigated the effects of the additional length scale parameter and elastic foundation on the bending, buckling and vibration of a thin microplate mounted on an elastic Winkler foundation.

In recent years, the study of fluid-structure interaction (FSI) is increased. It is well known that the vibration behavior of plates, totally or partially immersed in fluid, is certainly distinct from those in air. This is due to the fact that the existence of fluid causes a noteworthy enhancement in the total kinetic energy of the plate. Consequently, the natural frequencies relating to wet modes decrease notably compared with those relating to dry modes. Some selected published papers for the plate models in contact with a fluid are reviewed here as follows. Bauer (1981) has presented an analytical solution for the vibration of an elastic bottom of a rectangular tank which has been filled with an ideal fluid. The simple end conditions have been considered for the plate. Vibrational characteristics of the vertical and horizontal square plates with fully clamped boundary conditions have been presented by Fu and Price (1987). The combination of the finite element method and a singularity panel distribution has been used by the authors. In another study, Zhou and Cheung (2000) have investigated the dynamic responses of an elastic plate which is in contact with an ideal fluid on one side by employing the Rayleigh-Ritz method. Ergin and Uğurlu (2003) have reported the natural frequencies and the corresponding mode shapes of cantilever plates contacting with a fluid. They have verified their results with the experimental data of Lindholm et al. (U. S. Lindholm et al., 1962), numerical data of Fu and Price (1987) and ANSYS (a finite element software). Khorshidi and Farhadi (2013) have carried out the free vibration analysis of a laminated composite rectangular plate partially or totally in contact with a finite fluid by using the Rayleigh-Ritz method. Uğurlu et al. (2008) and Hosseini-Hashemi et al. (2010) have examined the effects of Pasternak foundation and ideal fluid on the natural frequencies of rectangular Kirchhoff and Mindlin plates, respectively. Amabili (2000) has usefully considered the sloshing condition into the eigenvalue problems of vibrating structures contacting with stationary fluids and free surface area. Zhou and Liu (2007) have investigated the dynamic response of the flexible rectangular tanks partially filled with an ideal fluid. Taking into account the surface waves, bulging mode and sloshing mode, they have used a combination of the Rayleigh-Ritz method and the Galerkin method to obtain the solution. Liao and Ma (2016) have investigated the wet resonant frequencies and the corresponding mode shapes of a rectangular plate located at the rigid bottom slab of a container which is filled with non-viscose and compressible fluid. Kerboua et al. (2008) have presented a comprehensive investigation on the natural frequencies of rectangular plates contacting with fluid by adopting the so-called Hybrid approach. This approach is the combination of finite element framework and Sander's shell theory.

As can be seen the analysis of a macroplate in contact with a fluid and also the static and dynamic analysis of a microplate based on the modified couple stress theory have been investigated and well discussed by the researchers. To the best of the author's knowledge, there is only one research in which that the vibrational analysis of a microplates contacting with a fluid has been performed by Omiddezyani et al. (2017). The assumptions of Kirchhoff theory and also the modified couple stress theory have been used by the authors.

The purpose of this study is to investigate the size-effect and fluid-structure interaction on the vibrational characteristics of a rectangular microplate by taking into account the influences of rotary inertia and transverse shear deformation, which have the remarkable role in the analysis of moderately thick microplates. The first order shear deformation theory along with the modified couple stress theory has been used to perform the free vibrational analysis of the considered problem. By employing the Hamilton's principle, the non-classical equations of motion and also the corresponding boundary conditions are derived. Then the Rayleigh-Ritz method has been applied to calculate the natural frequencies of the system. Finally based on the obtained results, the effects of side to thickness ratio, aspect ratio, material length scale parameter and also the fluid height on the natural frequencies are discussed in detail.

2. Theoretical formulation

2.1. Modified couple stress theory

As mentioned earlier, the modified couple stress theory has been successfully clarified by Yang et al. (2002). According to this new theory, the couple stress tensor must be a symmetric tensor and since the strain energy U is assumed as an explicit function of strain tensor (conjugate with symmetric stress tensor) and symmetric curvature tensor (conjugate with deviatoric part of the couple stress tensor), there is only one material length scale parameter which is incorporated in the formulation of this theory.

The strain energy U of an isotropic linear elastic material is written as:

$$U = \frac{1}{2}\int_{\Lambda} (\overleftrightarrow{\sigma} : \overleftrightarrow{\varepsilon} + \overleftrightarrow{m} : \overleftrightarrow{\chi})d\Lambda \tag{1}$$

where $\overleftrightarrow{\sigma}$ is the symmetric stress tensor, $\overleftrightarrow{\varepsilon}$ is the strain tensor, $\overleftrightarrow{m}$ is the deviatoric part of the couple stress tensor and $\overleftrightarrow{\chi}$ is the symmetric curvature tensor which are respectively given by (Yang et al., 2002):

$$\overleftrightarrow{\sigma} = \lambda tr(\overleftrightarrow{\varepsilon})\overleftrightarrow{I} + 2\mu\overleftrightarrow{\varepsilon} \tag{2}$$

$$\overleftrightarrow{\varepsilon} = \frac{1}{2}[\nabla\vec{u} + (\nabla\vec{u})^{T}] \tag{3}$$

$$\overleftrightarrow{m} = 2l^2\mu\overleftrightarrow{\chi} \tag{4}$$