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Vibration and Stability Analysis of Micro-pipes Conveying Fluid under Magnetic, Electric, and Thermal Fields

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ABSTRACT: In this study, vibration and stability analysis of micro-pipes conveying fluid under magnetic, electric, and thermal fields using classical, modified coupled stress, and modified strain gradient theories are presented. The Euler-Bernoulli beam theory with clamped-pinned, clamped-clamped, and pinned-pinned boundary conditions is used for modeling the pipe. The differential equations governing the vibration of conveying fluid micro-pipe are derived through extended Hamilton's method. Additionally, the extended Galerkin's method is used to convert the governing partial differential equations into ordinary differential equations. The effects of size, boundary conditions, magnetic field, electric field, and thermal field on eigenvalues and critical velocity are investigated. The results indicated that the strain gradient theory predicts the highest natural frequencies and critical fluid velocities among the other two theories. The effects of magnetic, electric, and thermal fields along with different boundary conditions on eigenvalues and critical fluid velocity have been studied. It has also been concluded that the impact of these fields on the stability regions is different for different boundary conditions. Furthermore, the results showed that the stability of the micro-pipes increases with the increase of the magnetic field coefficient, but decreases with the increase of the coefficient of electric and thermal fields.

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1- Introduction

Micro-pipes and nanotubes have been widely used in micro-electrical and micro-mechanical systems such as sensors, stimulants, fluid transducers, and drug injection due to their geometry and mechanical properties [1]. In 2015, Abbas Nejad et al. [2] investigated the vibration and stability of a micro-pipe conveying fluid with piezoelectric layers. In 2016, Amiri et al. [3] studied the vibration and stability of the micro-pipe conveying fluid under magnetic, electric, and thermal field with the pinned-pinned and clamped–clamped boundary conditions.

Recently, there have been many studies on the vibration and stability of pipes conveying fluid on macro, micro, and nano scales [4, 5].

The novelties of the present study are the following:

- Micro-pipe vibration analysis and stability considering the modified strain gradient and coupling stress theories.
- Considering the effect of magnetic, electric, and thermal fields on vibration and micro-pipe stability conveying fluid for three boundary conditions; pinned-pinned, clamped-pinned, and clamped-clamped.
- Comparing the results for three theories of strain gradient, couple stress, and classical theory.

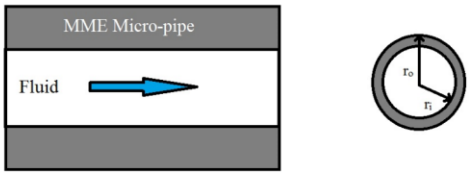

Fig. 1. Schematic of an MEE micro-pipe conveying fluid and its cross-sectional area.

2- Methodology

The schematic of the Magneto-Electro-Elastic (MEE) micro-pipe conveying incompressible fluid configuration under uniform temperature changes and external magnetoelectric potentials is shown in Fig. 1.

The equation of motion of the micro-pipe can be expressed as follows:

$$S\frac{\partial^4 W}{\partial x^4} - K\frac{\partial^6 W}{\partial x^6} + m_f V^2\frac{\partial^2 W}{\partial x^2} + 2m_f V\frac{\partial^2 W}{\partial x\,\partial t} + \left(m_f + m_p\right)\frac{\partial^2 W}{\partial t^2} + N\frac{\partial^2 W}{\partial x^2} = 0 \tag{1}$$

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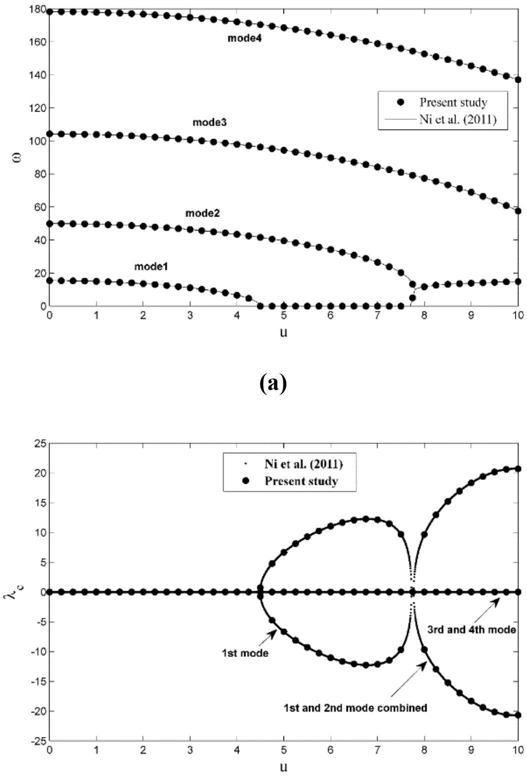


(a)

(b)

Fig. 2. Validation of the first four eigenvalues of clamped-pinned pipe (β=0.5), a) imaginary part b) real part

In addition, boundary conditions at *x=0, L* can be expressed as:

$$S\frac{\partial^3 W}{\partial x^3}-K\frac{\partial^5 W}{\partial x^5}+\left(m_f V^2+N\right)\frac{\partial W}{\partial x}+ m_f V\frac{\partial W}{\partial t}=0 \qquad or\ W=0$$

$$\left(S\frac{\partial^2 W}{\partial x^2}-K\frac{\partial^4 W}{\partial x^4}\right)=0 \qquad or\ W'=0 \tag{2}$$

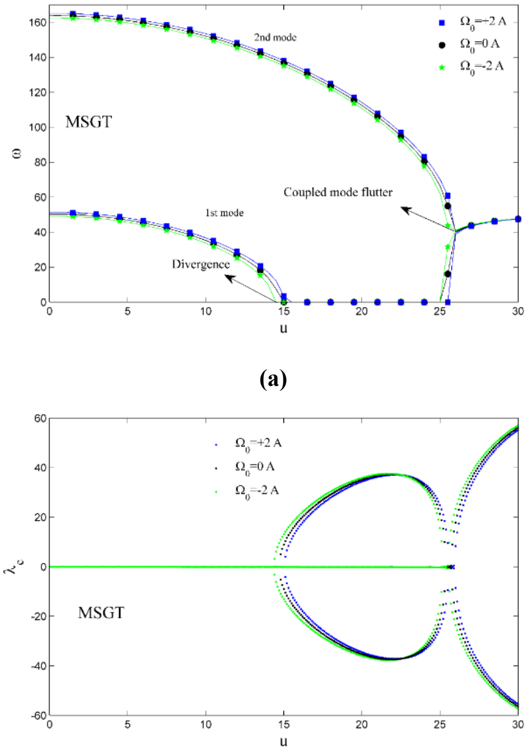
$$K\frac{\partial^3 W}{\partial x^3}=0 \qquad or\ W''=0$$

where $K=GI\left(2l_0^2+\frac{4}{5}l_1^2\right)$

$$S=E_{eff}\,I+GA\left(2l_0^2+\frac{8}{15}l_1^2+l_2^2\right)$$

and $N=N_e+N_m+N_t$.

The parameters $W, l_i\,(i=0,1,2), I, A$ and G are the transverse displacement of the micro-pipe, length scale parameters of the MEE micro-pipe, cross-sectional moment of inertia of the micro-pipe, the cross-sectional area of the micro-pipe, and the shear modulus respectively. In addition, effective elastic modules (E_{eff}) and the generated axial forces N_e, N_m and N_t due to the electric, magnetic, and temperature fields, respectively: can be obtained as



(a)

(b)

Fig. 3. Effect of magnetic field parameter on (a) imaginary part and (b) real part of eigenvalues of clamped-pinned boundary condition for Modified Strain Gradient theory and for (β = 0.64)

$$\begin{aligned}
&E_{eff}=c_{11}+e_{31}M_1+f_{31}M_2\\
&M_1=\frac{\mu_{33}e_{31}-g_{33}f_{31}}{h_{33}\mu_{33}-g_{33}^2},\\
&M_2=\frac{h_{33}f_{31}-g_{33}e_{31}}{h_{33}\mu_{33}-g_{33}^2},\\
&N_e=-2\pi Re_{31}V_0\,,N_m=-2\pi Rf_{31}\Omega_0,\\
&N_t=2\pi R\,\beta_1 h\,\Delta T
\end{aligned} \tag{3}$$

where $c_{11}, e_{31}, h_{33}, f_{31}, g_{33}, \mu_{33}$ and β_1 indicate elastic, piezoelectric, dielectric, piezomagnetic, magnetoelectric, magnetic permeability, and thermal moduli constants for the MEE material, respectively.

3- Results and Discussion

Fig. 2 presents the results of this research and compares them with those presented in Ref. [6]. The imaginary and real parts of eigenvalues are illustrated in Figs. 2(a) and 2(b), respectively, and compared to the results of Ni et al. [6] (2011). It is seen from Fig. 2 that the current model is actually in good agreement with previous models.

In this section, a numerical analysis of the vibrational behavior of MEE micro-pipes is presented. The fluid density, mean radius, thickness, and slender ratio (Length to mean radius) of the micro-pipe are assumed to be $\rho = 1000\text{kg/m}^3$, R = $20\mu m$, $h=2\mu m$ and $L/R=20$, respectively. Also, the other data for material properties of the considered MEE micro-pipe are taken from Ref. [3].

In addition, the mass ratio (β) in this study is 0.64, and the values of l_0, l_1 and l_2 are $17.6\times10^{-6}\,\text{m}$. In this section, the influence of magnetic, electric, and thermal fields parameters on the imaginary and real parts of eigenvalues for the two first modes of a clamped-pinned micro-pipe conveying fluid is investigated.

The effect of the magnetic field on the imaginary part of the eigenvalue for the clamped-pinned boundary condition using modified strain gradient theory is considered in Fig. 3(a). It can be seen that increasing the magnetic field parameter increases the velocity at which the divergence or flutter of the coupled mode occurs. So it improves the stability behavior of the system. These effects can also be seen in the real part of those eigenvalues in Fig. 3(b). This is because the tensile and compressive forces in the micro-pipe are created by applying a positive and negative magnetic field, respectively. In other words, as the positive magnetic potential increases, the stiffness of the micro-pipe increases. Subsequently, critical velocity also increases.

4- Conclusions

In this research, the vibration and stability of a micro-pipe conveying fluid under external fields are studied. The results show that the positive magnetic field leads to higher stability of the micro-pipe. Whereas positive electric and thermal fields result in a decrease in the stable region of the micro-pipe. This is because tensile and compressive forces in the micro-pipe are created by applying a positive and negative magnetic field, respectively. Because an increase in positive magnetic potential yields an increase in micro-pipe stiffness and consequently increases critical flow velocity. However, an increase in positive electric and thermal fields creates compressive forces, which leads to a decrease in system stiffness and as a result reduces the stability of the system. Furthermore, the analysis of results for classical, modified couple stress, and modified strain gradient theories reveals that the highest and lowest stability regions are predicted by strain gradient and classical theories, respectively.

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