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Stability analysis of composite thin-walled pipes conveying fluid

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ABSTRACT

Stability analysis of a composite thin-walled cantilever pipe conveying fluid supported at free end by linear translational and rotational springs is considered in this paper. The governing equations of the system are developed by extended Hamilton's principle for open systems. Applying extended Galerkin technique, eigenvalue analysis is implemented and the critical fluid velocity and consequently stability of the system are obtained. The critical velocity and eigenvalue are validated by comparison with the results in available literature. The numerical results are presented to investigate the effects of fiber orientation angle, volume fraction of fiber, composite lay-up, size of fiber, structural damping coefficient, mass fluid ratio and elastic boundary conditions on eigenvalue and critical fluid velocity of the system. It is revealed that by increasing the value of fiber orientation angle, the critical fluid velocity of the system is decreased. Furthermore, it is found that the volume fraction of fiber and size of fiber have stabilizing effects on the dynamic behavior of the system. Moreover, it is demonstrated that by increasing the value of linear spring constant at the free end, the pipe loses stability by either divergence or flutter.

1. Introduction

Flow-induced vibration of flexible pipe with flowing fluid is a fundamental dynamical problem in the field of fluid-structure interactions (Paidoussis, 1998). Pipes conveying fluid are common elements in numerous engineering applications, as well as serving as a model for understanding systems that are more complex and for searching new dynamic features and phenomena. In some papers (Ibrahim, 2010, 2011; Ni et al., 2011; Païdoussis and Li, 1993; Parameshwaran et al., 2016; Ryu et al., 2002) a perspective review of the available investigation on this dynamical problem was presented. Ni et al. (2011) addressed the vibration analysis of fluid-conveying pipes with different boundary conditions using differential transformation method. The effects of internal moving fluid, end-nozzle inclination angle and the nozzle aspect ratio on the flutter instability of cantilever pipes was studied by Firouz-Abadi et al. (2013). A numerical method was developed by Yu et al. (2013), the so-called transfer matrix method, to analyze the stability problem of fluid-conveying periodic pipes. The periodic variations of either geometrical or material properties was taken into account in their research. Dai et al. (2013) studied the vibration and instability of fluid-conveying pipes consisting of two segments made of different materials. The influences of the fluid flow, temperature gradient, volume fraction indexes of functionally graded materials (FGMs) and compressive axial load on the divergence and flutter boundaries of thin-walled FGM pipes conveying fluid were investigated (Eftekhari and Hosseini, 2015; Hosseini and Fazelzadeh, 2011). Shen et al. (2014b) investigated the stability of periodic FGM shells with flowing fluid and explored the influences of fluid velocity, mass ratio, lengths of segments and grading profiles on the vibration behavior. The effects of the fluid velocity, mass fluid ratio and power law exponent on the divergence and couple mode flutter velocities of a FGM pipe containing fluid flow have been pursued by Wang and Liu (2016). Furthermore, vibration and dynamics of pipes conveying fluid also have been discussed in Refs. (Bahaadini and Hosseini, 2018; Bahaadini et al., 2017, 2018; Dai et al., 2014; Gu et al., 2016; Hosseini et al., 2016; Jafari-Talookolaei and Lasemi-Imani, 2015; Kaewunruen et al., 2005; Meng et al., 2017; Zare et al., 2017; Zhou et al., 2017). Here we study a similar problem, find critical flutter velocity in a cantilever pipe conveying fluid. According to literature review, it is noted that the vibration and instability behaviors of isotropic pipe conveying fluid have been investigated. However, some studies have conducted vibration analyses of the pipe made of FGM. In current work, stability analysis of composite thin-walled

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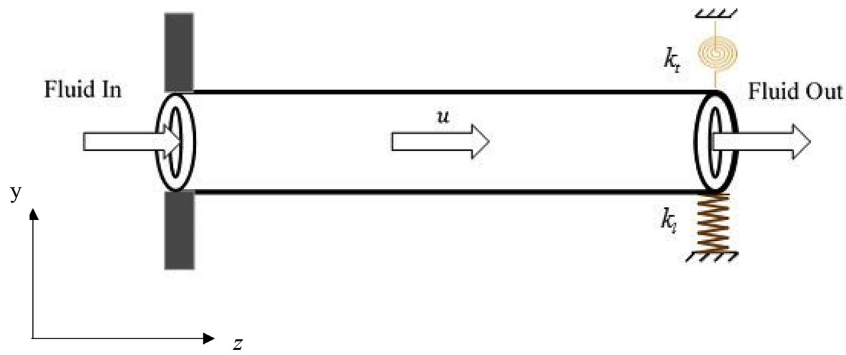
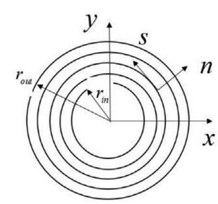


(a)



(b)

Fig. 1. A cantilever composite thin-walled pipe conveying fluid with elastic boundary condition at the free end: (a) geometry and coordinate system and (b) the cross section of pipe.

Table 1
Values for physical parameter of composite pipe conveying fluid (Kim and Lee, 2014).

Physical properties and parameters	Values (graphite/epoxy)	
Elastic modulus, E (GPa)	$E_{11} = 144$	$E_{22} = 9.65$
Shear modulus, G (GPa)	$G_{12} = 4.14$	
Poisson ratio, v	$v_{12} = 0.3$	
Pipe density, ρ_p ($\frac{kg}{m^3}$)	1389	
Inner diameter, r_{in} (m)	0.2	
The thickness of each layer, h (m)	0.0075	
Length, L (m)	12	
Fluid density, ρ_f($\frac{kg}{m^3}$)	1.6	

cantilever pipe containing fluid flow is studied. Besides, the effects of fiber orientation angle, volume fraction of fiber, symmetric composite lay-up, size of fiber and elastic boundary conditions on eigenvalue and critical fluid velocity of the system have been investigated.

Cantilever pipe conveying fluid systems by the addition of spring supports may lose stability by both flutter and divergence. Therefore, it has been a subject of great interest and a challenging research topic over the past few decades. Chen and Fan (1987) studied the cantilever pipe additionally supported at the free end by a translational spring. It was found that the dynamic interaction of the pipe and the spring may render the system unstable in the form of divergence or flutter depending on the spring stiffness. Several studies were conducted to examine the effect of spring support on the vibration and stability of pipe conveying fluid; see, for example, Noah and Hopkins (1980), Edelstein and Chen (1985), Sugiyama et al. (1985), Païdoussis et al. (2007), Ghayesh and Païdoussis (2010), Ghayesh et al. (2011) and Hosseini et al. (2018). Recently, Shen et al. (2014a), in the context of the Flügge shell theory, have studied the effects of internal moving fluid, geometric shape, material parameters and spring supports on the stability of periodic FGM shells conveying fluid. To analyze the dynamics of fluid-conveying pipes, Kheiri et al. (2014) have tried to establish the governing equations and boundary

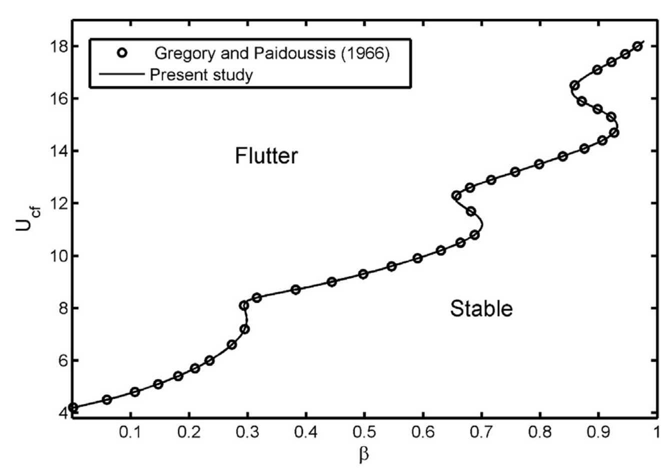


Fig. 2. Comparison of the critical flutter velocity of cantilever isotropic pipe with those reported by Gregory and Paidoussis (1966) for $K_l = K_t = 0$ and $\alpha = 0$.

conditions of Euler-Bernoulli beam by means of the elastic boundary conditions.

Thin-walled beams made of fiber reinforced composite materials have found wide applications in designing composite pipelines, wind turbine rotor blades, aircraft wings and helicopter rotor blades because of their superior mechanical properties such as high strength/stiffness to weight ratios and favorable fatigue characteristics (Librescu and Song, 2005; Oh et al., 2005; Song and Librescu, 1993). In relation to composite thin-walled pipes, Khulief et al. (2015) calculated the modal frequency of the composite thin-walled pipe based on the wavelet-based finite element model. They verified the numerical result of the effect of the induced thinning on the natural frequencies with experimental test. Oke and Khulief (2016) used the nonlocal B-spline wavelets finite element method to examine the numerical solutions for the vibration analysis of