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Natural frequency and stability analysis of a pipe conveying fluid with axially moving supports immersed in fluid

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ABSTRACT

Structural model for a slender and uniform pipe conveying fluid, with axially moving supports on both ends, immersed in an incompressible fluid, is formulated. Free vibration and stability of the system are studied through numerical calculation. First, the equations of motion of the system are derived in an absolute coordinate system. An "axial added mass coefficient" is adopted to amend the forces caused by the external fluid. Boundary conditions are fixed by using coordinated conversion. Then, numerical results of the natural frequency are obtained via the Galerkin method, both for pinned-pinned and clamped-clamped supports. The critical speeds of supports and several instability types are discussed. Last, the effects of the system parameters on the dynamics and instability of the system are investigated.

1. Introduction

Axially moving systems widely exist in the engineering devices (e.g. robot system, space structure, conveyor belts, chains drives, underwater pipeline, etc.). The wide applications have motivated intense research activity. Mote [1] approximately calculated the fundamental frequencies of several axially moving materials through the Galerkin method, and the results were confirmed by the following experiment by Mote and Naguleswarn [2]. Mote [3] also investigated the dynamic stability of these axially moving systems. Later on, Öz and his co-workers [4–7] studied the natural frequencies and stability regions of an axially moving elastic pipe. More recently, Païdoussis [8,9] performed a concise review of the earlier researches on the extruding materials. Two nonlinear models of axially moving beams were investigated by Ding and Chen [10], and the natural frequencies of these two models were also studied via the fast Fourier transform (FFT) [11]. Ghayesh and his co-workers [12–14] analytically and numerically studied the nonlinear dynamics of axially moving strings and beams through different methods.

In the studies on axially moving material mentioned above, the supports of these systems are fixed. In fact, the motion of the supports may also bring out the axial movement of strings or beams. The dynamic behavior of flexible bodies with moving supports has been studied for decades in so many areas, such as machine design, robot technology, aircraft and spacecraft design. Balakrishnan [15] made an excellent review on the large space structure problems. Kane [16] studied the dynamic behaviors of a cantilever beam which built to a moving base. Du et al. [17] presented a finite element structural dynamics model of a three-dimensional elastic beam with an arbitrary moving base through the lumped mass method. Later

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on, a review on flexible multi-body dynamics was presented by Shabana [18]. Hyun and Yoo [19] investigated the stability of axially oscillating cantilever beams. Liu et al. [20] derived an exact nonlinear hybrid-coordinate formulation for flexible multi-body systems by using the virtual work principle. Yoo et al. [21] studied the stability of a cantilever beam attached to a rigid base which motivated by a harmonic motion. More recently, Gerstmayr et al. [22] presented a review on the application of the finite element absolute nodal coordinate formulation in analysis of large deformation constrained multi-body systems.

In the works mentioned above, the axially moving materials were considered without surrounding fluid. However, in the engineering practice such as aerospace engineering and underwater engineering, the influences of the surrounding fluid were hard to be ignored. The dynamics and stability of a uniform slender cantilever beam which extending axially and immersing in an incompressible fluid were studied by Taleb and Misra [23]. Subsequently, Gosselin et al. [24] proved that the fluid-dynamic forces calculated by Taleb and Misra [23] were not accurate enough. An "axial added mass coefficient" was introduced by Gosselin et al. [24] to better approximate the mass of the external fluid which stayed attached to the axially moving beam, so that the fluid-dynamic forces caused by the external fluid could be calculated more precisely. After that, Wang and Ni [25] studied the inherent frequency and stability of an axially moving beam immersed in fluid through Differential Quadrature Method (DQM). In the aspect of engineering application, Hellum et al. [26,27] investigated the dynamics of a submersible (considered as rigid body) propelled by a fluttering fluid-conveying tail by modeling and simulation. Most lately, in order to study the flight-refueling system, Ni and Li [28,29] investigated the dynamics of a slender beam with surrounding fluid, under different boundary conditions (cantilever or both ends supported), and Yan [30] improved the system to an extending beam attached to an axially moving base. But in practice, the flight-refueling system was more like a pipe conveying fluid system, which meant the fluid-structure interaction caused by the internal flow cannot be ignored. As mentioned above, there were many researches on the dynamics of the beam structures attached to moving supports immersed in fluid, but few researches on those of the pipe structures. Huo [31] studied the dynamic of a vertically deploying/retracting cantilevered pipe conveying fluid, but in his work, the surrounding fluid was not considered.

In the present study, a uniform slender pipe conveying fluid system with axially moving supports is considered, and the whole system is immersed in an incompressible fluid. First, the equations of motion of the pipe system are derived. Then, the discrete equations of motion are derived using the Galerkin method. Before numerical computation, the convergence of the Galerkin method and the validation of the model are discussed. Last, the natural frequencies of the pipe system and the critical instability speed of the supports, with different internal fluid velocities, are obtained; the instability region of the pipe system is analyzed and several instability types are discussed; and the influences of some system parameters (e.g. the internal fluid velocity, the slender ratio of the pipe, the added axial mass coefficient and the dimensionless initial tension) on the vibration and stability of the system are also investigated.

2. Systematic formulation and theoretical derivation

The system to be analyzed is shown in Fig. 1. It consists of a uniform pipe of outer diameter D, length l, internal perimeter S, mass per unit length m_p, flexural rigidity EI, internal cross-sectional area A_i and conveying fluid of mass per unit length m_f, with mean axial flow velocity V relative to the pipe, the fluid pressure p_i. The pipe attaches to axially moving supports and the supports move at an axial speed $\dot{L}(t)$. The whole system is immersed in an incompressible fluid of density ρ, the effect of the boundaries can be neglected. In this paper, it is supposed that there is no separation occurs in the cross-flow, and the fluid forces acting on a pipe element are the same as those acting on a corresponding element of a long undeformed pipe of the same cross-sectional area and inclination.

Based on the study of Ni and Li [28,29], two coordinate systems are set up to better describe the motion of the pipe system, the absolute coordinate system (x, z) and the moving coordinate system $(\bar{x}, \bar{z})$ fixed at the supports. The equations of motion of the pipe system are derived in the absolute coordinate system first. Then, in order to fix the boundary of the pipe, the coordinate transformation between the two coordinate systems is made. After that, in the moving coordinate, the equations of motion of the pipe system are derived.

In the absolute coordinate system (x, z), the motions of the pipe is denoted as axial displacement $u(x, t)$ and the transverse displacement $w(x, t)$. The axial displacement of the pipe can be separated into two parts: the motion attached to the support and the axial deformation of the pipe

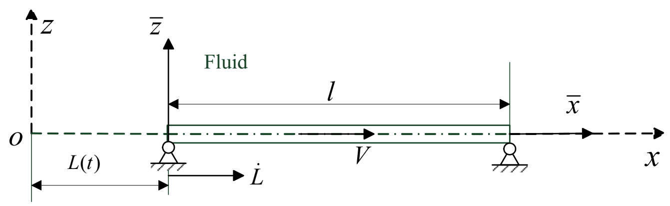

Fig. 1. The analysis system and the corresponding coordinates.