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Nonlinear dynamics of a sliding pipe conveying fluid

Hao Yan [a], Huliang Dai [a,b], Qiao Ni [a,b,*], Lin Wang [a,b], Yikun Wang [a]

[a] Department of Mechanics, Huazhong University of Science and Technology, Wuhan 430074, China
[b] Hubei Key Laboratory for Engineering Structural Analysis and Safety Assessment, Wuhan 430074, China

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ABSTRACT

In this study, nonlinear analysis on dynamic responses of a sliding fluid conveying pipe with length time-varying is performed in detail. An extended Hamilton's principle is utilized to derive the nonlinear governing equation of motion for the pipe system. Subsequently, effects of flow velocity, sliding rate and two key parameters, e.g. mass ratio and gravity, on dynamic behavior of the pipe are elaborately addressed. The obtained results indicate that the dynamics and stabilities of the pipe system are quite sensitive to the flow velocity, which is dependent on different values of the sliding rate. As the flow velocity is beyond the critical value, flutter occurs and this flutter amplitude of pipe changes with time going on. In addition, it is shown that the pipe becomes easier to lose stability with the increase of the sliding rate, while increasing the mass ratio and gravity of the pipe can enhance its stability.

1. Introduction

Studies on axially moving of slender structures have received a great interest in several areas of engineering applications during the past decades (Kaczmarczyk and Ostachowicz, 2003; Sandilo and Van Horssen, 2012; Suweken and Van Horssen, 2003; Zhu and Chen, 2005). Examples are band saws, elevator cables, probe and drogue in aerial refueling, machine tools and deployable space structures. An extensive and intensive understanding of such research field can be referred to reviews by Mote (1972) and Wicker and Mote (1988).

Carrier (1949) and Tabarrok et al. (1974) were the first to investigate the dynamics of axially moving strings and beams. Thereafter, increasing researches on this topic were performed. For instance, dynamic behaviors of an axially moving flexible robot arm were explored by Wang and Wei (1987). Taleb and Misra (1981) and Gosselin et al. (2007) studied the dynamics and stability of a deploying/extruding beam in the dense fluid. Inspired by the propulsion through trichocyst extrusion in paramecium, Gosselin et al. (2014) proposed an experiment and conducted a numerical model to study the stability of a slender beam extruded in a highly viscous fluid. They found that the beam can buckle at a critical length based on the extrusion speed, bending rigidity, and viscosity of the fluid. By considering an axially moving base, dynamic responses of an extending beam attached to the moving base in the dense fluid was investigated by Yan et al. (2016). Rich dynamics were found in such a system. In addition, dynamic behaviors of translating beams and strings with arbitrary varying length were successively investigated by Zhu and Ni (1999), Zhu et al. (2001) and Zhu and Zheng (2008). However, it should be mentioned that these significant works mentioned above focused on linear dynamics, few researches investigated the nonlinear dynamic responses of axially moving beams. Behdinan et al. (1997) and Behdinan and Tabarrok (1997) conducted the nonlinear analysis for flexible sliding beams. They derived equations of motion using the extended Hamilton's principle and discretized it by Galerkin method. Some other nonlinear analyses for axially moving structures have been addressed by

* Corresponding author at: Department of Mechanics, Huazhong University of Science and Technology, Wuhan 430074, China.
E-mail address: niqiao@hust.edu.cn (Q. Ni).

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Stolte and Benson (1992, 1993), Vu-Quoc and Li (1995) and Mansfield and Simmonds (1987) and Park et al. (2013). What is more, a novel idea was proposed by Vu-Quoc and Li (1995) who introduced the so called geometrically exact beam theory and took large angle maneuvers into consideration in the analysis for this system. A comprehensive survey on the latest progresses on the nonlinear dynamics of transverse motion of axially moving strings and belts can be referred to Chen et al. (2009).

As another typical flexible slender structure, pipes conveying fluid also received wide concerns in research interests due to their broad applications in engineering fields (Łuczko and Czerwiński, 2017; Paï doussis, 1998; Rivero-Rodriguez and Pérez-Saborid, 2015; Texier and Dorbolo, 2015). Except that the length of pipes/risers conveying fluid is mostly constant in engineering, in some other applications, the pipe length can be varying. For example, the feeding pipe in the casting and filling process has the characteristic of time varying in length. The feeding pipe is often required to extrude or retract to guarantee that its tip to be always close to the liquid surface for avoiding the liquid splashing and ensuring the filling speed simultaneously (Huo and Wang, 2016). Moreover, the earth drilling apparatus is another good example. During drilling process, a drilling bit is driven by a rotating drill pipe which extends through the central opening of a well. Then the drilling fluid is centrally passed through the drill pipe to remove the cuttings. This can be simplified to a model of an extruding pipe conveying fluid. It is worth mentioning that, a linear analysis of a vertically deploying/retracting cantilevered pipe conveying fluid was recently investigated by Huo and Wang (2016), who proposed a linear theoretical model for this time-varying length pipe conveying fluid and found that the stability of the pipe system can be significantly affected by the flow velocity, gravity, instantaneous length of the pipe and the mass ratio. Different from previous studies which only proposed a linear governing equation and conducted a linear analysis, this work constructed a nonlinear governing equation and did a nonlinear analysis which helped us to investigate the dynamics of this time-varying length pipe conveying fluid system more accurate, focusing on the effects of sliding rate and flow velocity on the dynamical responses of the pipe system.

In the present work, a nonlinear governing equation of motion for a sliding pipe conveying fluid is derived based on the extended Hamilton's principle. Linear and nonlinear analyses are both elaborately conducted to investigate stability and dynamical behaviors of the system. Furthermore, parameter analysis is performed to examine its influence on the stability of the pipe system. Finally, some important conclusions are drawn out.

2. Modeling of the nonlinear governing equation

We consider a uniform cantilevered fluid-conveying pipe which is able to slide from the fixed channel with a rate $\dot{L}(t)$. $L(t)$ means the length of the pipe outside the channel, as shown in Fig. 1. It is noted that the length is time-varying. Considering the pipe with flow area A, flexural rigidity EI, mass per unit length m. The mass of fluid per unit length is M. Defining U as the axial flow velocity related to the sliding pipe. It is noted that the sliding rate of pipe is usually much smaller compared to the flow velocity in practical engineering applications, hence we consider $\dot{L}(t) \ll U$ here. Assuming the fluid flows in the pipe as fully developed turbulent-flow. The pipe is slender and behaves as Euler–Bernoulli beam. Although deflections are large, the strain in the pipe is assumed to be small. In addition, the transverse displacement $w(x, t)$ is assumed to be of order one magnitude and the energy terms are built to be of order four magnitude, hence the equations of motion become of order three magnitude.

It is natural and convenient to describe motions of the pipe through three different configurations when the pipe is sliding at any instant, namely, the initial undeformed pipe or material configuration in the channel, sliding undeformed pipe or the spatially fixed intermediate configuration and the sliding deformed configuration (Vu-Quoc and Li, 1995), which is shown in Fig. 1. Indeed, the intermediate configuration does not appear in reality. That is to say, the motion of pipe cannot experience a sequence of configurations from the initial to the intermediate and finally to the deformed configuration. However, it requires a sliding undeformed configuration as a reference status to describe the sliding deformed configuration. Therefore the intermediate configuration is introduced here (Behdinan et al., 1997; Behdinan and Tabarrok, 1997).

For the intermediate configuration of pipe system, we note that its free boundary is extending with time going on. This configuration can be considered as a Lagrangian domain with respect to the current deformed pipe and an Eulerian domain with respect to the sliding undeformed pipe.

We focus on the part of the sliding pipe outside the channel, since the part inside the channel is non-deformable and has a prescribed motion. Consequently, the task is to analyze the motion of pipe as it extrudes from the channel.

2.1. Description of the Kinematic analysis

In order to describe the kinematics of the deformed pipe, two sets of coordinate systems are chosen. As shown in Fig. 2, the Eulerian coordinates (x, y) is utilized to describe a material point $p(x, y)$ in the deformed state, and the Lagrangian coordinate (X, Y) is utilized to describe the corresponding material point $p_0(X, Y)$ in the undeformed state. It should be noted that the X-axis is superposed on the x-axis along which is the equilibrium configuration. Hence we have $(X, Y) = (X, 0)$. Then, its deflection is

$$u = x - X \text{ and } w = y - Y = y \tag{1}$$

Since the pipe can be viewed as a clamped-free type, it is customary and useful to introduce a curvilinear coordinate s, along the length of the pipe.