Journal of Sound and Vibration 383 (2016) 364–383

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Dynamics and stability of an extending beam attached to an axially moving base immersed in dense fluid

H. Yan [a], Q. Ni [a,b,*], H.L. Dai [a,b], L. Wang [a,b], M. Li [c], Y. Wang [a], Y. Luo [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
[c] Department of Engineering Mechanics, Dalian University of Technology, Dalian 116024, China

ARTICLE INFO

Article history:
Received 22 November 2015
Received in revised form
29 June 2016
Accepted 20 July 2016
Handling Editor: S. Ilanko
Available online 11 August 2016

Keywords:
Cantilevered beam
Dynamic behavior
Axially extending
Peak response

ABSTRACT

In the present study, we construct a theoretical model for investigating the dynamics and stability of a flexible slender cantilever which is attached to an axially moving base fully immersed in an incompressible fluid. Meanwhile, the cantilevered beam is subjected to a time dependent axial extension. The coordinate transformation is utilized to derive the governing equations with consideration of an axial added mass coefficient and realistic initial conditions. Based on the Galerkin approach and Runge–Kutta technique, the numerical results for the dynamical behavior of the system under conditions of steady rate of extension and speed of the moving base are displayed. It is demonstrated that there is a critical value of extension rate at which the beam loses stability in the case when the base is fixed. As the base moves beyond a certain speed, however, the beam returns to be stable even if the extension rate is above the critical value. Furthermore, the beam system can exhibit peak response as the base moving speed is much higher than the extension rate.

1. Introduction

Due to wide applications in many kinds of engineering fields [1,2], including the extrusion processes, deployment of appendages in space, telescopic members of loading vehicles, robotic manipulators, and machine tools, dynamical behaviors of axially moving strings and beams have received the attention of many researchers. A good knowledge in the domain of axially moving structures can be gained from Mote [3] and Ulsoy et al. [4]. Early works were mainly motivated due to the dynamics of the band saws, chains, and belts in mechanical machinery and the vibrations of moving thread lines in the textile industry. Recently, Wickert and Mote [5] presented a review of literature in this domain. A comprehensive review on the issue of extruding beams is provided by Païdoussis [1].

A model for the transverse vibration of an axially moving beam with consideration of elastic coupling effect between two adjacent spans was treated by Ulsoy [6]. Tabarrok and Maraghy [7] and Hyun [8] investigated the stability characteristic and vibrating amplitude of an axially moving beam for different values of excitation frequency. Chen and Yang [9] evaluated the boundary of stability conditions of an axially moving visco-elastic beam and its nonlinear dynamics. Öz and his co-workers [10–13] obtained the modal functions and natural frequencies of axially moving elastic beams, taking into account of the

* Corresponding author at: Department of Mechanics, Huazhong University of Science and Technology, Wuhan 430074, China. Fax: +86 27 87543438.
E-mail address: niqiao@hust.edu.cn (Q. Ni).

http://dx.doi.org/10.1016/j.jsv.2016.07.029
0022-460X/

hinged–hinged and clamped–clamped ends conditions. Theoretical studies on the band vibration and stability of axially moving system was performed by Ulsoy and Mote [14]. They found that the band natural frequency of the system decreases with increasing axial velocity and increases with increasing axial tension or "strain". Li and Wang [15] studied the stability and nonlinear vibrations of a deploying flexible beam by using Lyapunov direct method. Kalaycioglu and Misra [16] presented approximate analytical solutions used as benchmarks to check numerical solutions for beam-type appendage deployment and tethered system deployment. The dynamics of deployable antennas was also studied by Tabarrok and Behdinan [17].

In recent years, however, researches on the dynamics of axially moving beam immersed in fluid have been developed and proceeded, which is quite different from those in the case where there was no fluid surrounding the moving beam or, if there was, it was ignored, as mentioned above. Taleb and Misra [18] investigated the dynamics of a cantilevered beam with uniform circular cross-section being deployed in a dense incompressible fluid. Subsequently, Gosselin et al. [19] tackled the same problem as that in Taleb and Misra [18] and proved that the fluid-dynamic forces used by Taleb and Misra [18] were not accurate enough. They introduced an "axial added mass coefficient" which can better approximate the surrounding fluid force acting on the cantilevered beam. Based on Galerkin's procedure, the natural frequencies and dynamic response of an axially moving cantilever beam were obtained. Then, Wang and Ni [20] studied the vibration and stability for an axially moving beam in fluid which is constrained by simple supports with torsion springs. Numerical results for the natural frequency for the axially moving beam by using the differential quadrature method (DQM) were obtained. More recently, Ni et al. [21] investigated the stability of a cantilever beam attached to an axially moving base immersed in fluid. Gosselin et al. [22] were inspired by the propulsion through trichocyst extrusion in paramecium, and proposed an experiment and conducted a numerical model to study the stability of a slender beam extruded in a highly viscous fluid. The natural frequency of the beam system has been numerically analyzed. Li [23] investigated the nonlinear dynamic behavior of a towed underwater beam with two supported ends and detected period-1, period-3, period-5, quasiperiodic and chaotic motions.

It should be noted that most of the available studies on axially moving beams immersed in fluid just considered one case, that is, either the axial motion of the structures induced by the axial movements of the supports, or the deploying/extruding beam with fixed supports. To the best of authors' knowledge, there has not been many into account of combining these two cases for investigating such issue of fluid-structure interactions, namely, beams with time dependent rate of extension and at the same time with axially moving support. In fact, many structures in engineering applications have such a behavior, for example, the probe structure in aerial refueling [24]. Before the probe connects to the drogue, it will extend from the tanker aircraft until reaching a certain length while the aircraft is still advancing. Then, the probe shrinks as refueling is completed. Inspired by this, we study the stability and dynamics of the deploying/extruding beam attached to an axially moving base and immersed in a dense incompressible fluid.

In the present study, firstly, we derive the governing equations of motion of a flexible slender cantilever with uniform circular cross-section, which extends axially in a horizontal plane at a known rate and at the same time attached to an axially moving base. The extending beam and the axially moving base are both immersed in an incompressible fluid. Then, the Galerkin method is utilized to discretize the partial differential equation (PDE) of motion into ordinary differential equation (ODE). Subsequently, the dynamical behavior of the fluid-structure coupling system is analyzed for different cases of extension rates of the beam and moving speeds of the base by evaluating the modal displacement, bending energy and natural frequency. Furthermore, parameter analysis is performed to examine its effect on the stability of the beam system. Finally, some important conclusions are drawn out.

2. Constructing the governing equation of motion

We consider a uniform cylindrical cantilever beam which is axially extending in a nominally horizontal direction with a rate $\dot{l}$. Meanwhile, the beam is attached to an axially moving base with a given motion $L(t)$. Let the beam be of diameter D, with area moment of inertia I, mass per unit length m, and modulus of elasticity E. The considered system, as shown in Fig. 1 is fully immersed in an incompressible fluid of density ρ. We assume the fluid boundaries are sufficiently distant so that they have negligible effect on the fluid forces which are acting the beam system. It is further assumed that no separation phenomenon occurs around the beam in the cross-flow direction because the lateral motion is small. The forces of the fluid

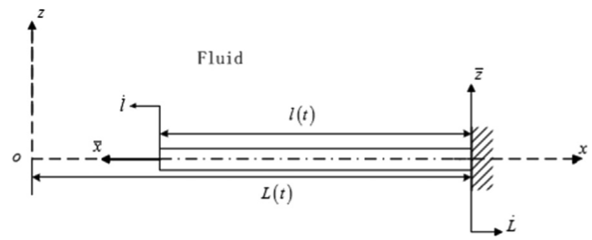

Fig. 1. Schematic of the extending cantilever beam attached to an axially moving base immersed in fluid.