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Free vibration and stability of a cantilever beam attached to an axially moving base immersed in fluid

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ABSTRACT

Free vibration and stability are investigated for a cantilever beam attached to an axially moving base in fluid. The equations of motion of the slender cantilever beam affiliated to an axially moving base at a known rate while immersed in an incompressible fluid are derived first. An "axially added mass coefficient" is taken into account in the obtained equations. Then, a coordinate transformation is introduced to fix the boundaries. Based on the Galerkin approach, the natural frequencies of the beam system are numerically analyzed. The effects of moving speed of the base and several other system parameters on the dynamics and stability of the beam are discussed in detail. It is found that when the moving speed exceeds a certain value the beam becomes unstable and the instability type is sensitive to the system parameters. When the values of system parameters, such as mass ratio and axially added mass coefficient, are big enough, however, no instabilities are detected. The variations of the lowest unstable critical moving speed with respect to several key parameters are also investigated.

1. Introduction

Dynamical behavior of axially moving system has attracted much attention because of their applications in many fields. The boundaries of the axially moving system are either free or supported. According to the supports of such system being fixed or not, the axially moving systems can be divided into two classes: first, systems with fixed and unmovable support; and second, systems that the axial motion of the structures is induced by the axial movements of the supports. There are big differences between these two types of axially moving system although these two kinds of systems seem to be similar.

It is noted that the axially moving system with fixed support can be further classified into two types, namely, the cantilever system and the supported system (both two ends are supported). Some examples of engineering applications of the cantilever system include, but are not limited to, deploying/extruding process [1–3]. The effective length of the axial moving cantilever beam is time-dependent in the moving process since the base is fixed [2,3]. In fact, the axially moving systems with both ends supported are just similar to the control volume of fluid dynamics because the particles contained in the supported system are changed in the moving process. Related engineering applications of the supported system include power transmission band, belt saws, aerial cable tramways, and elevator cables.

The linear and nonlinear dynamics of the supported axially moving materials with fixed support ends have been investigated by many researchers. Some extensive reviews on this subject can be found in [4,5]. The linear vibrations of band

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saw [6,7], axially moving elastic beams [8–11] were obtained by various methods. The pipe conveying fluid can be modeled as an axially moving string if the flexural stiffness vanishes. Based on this, the nonlinear vibrations and stabilities of tensioned pipes conveying fluid with variable velocity were explored by Öz [12]. Recently, the nonlinear dynamics of axially moving beams have attracted much attention [13–18]. Bağdatli et al. [19] studied the dynamics of axially moving beams using the method of multiple scales, with the consideration of the intermediate support.

In connection with a number of diverse disciplines, such as robotics and aircraft dynamics, the studies of slender beam attached to axially moving supports, which belongs to the axially moving system with axially moving support (i.e. the second types of axially moving system), have been vigorously pursued for several decades. Kane et al. [20] explored the dynamics of a cantilever beam attached to a moving base. Yoo and his co-works [21,22] investigated the linear stability of a cantilever beam subjected to axially oscillating base by Kane′s method. Feng and Hu [23,24] developed a set of nonlinear differential equations by using Kane′s method for the planar oscillation of slender beams subjected to a parametric excitation through the base movement, with the consideration of cubic geometrical and inertia nonlinearities.

To date, only few works can be found on the axially moving system with the consideration of the fluid–structure interaction. Taleb and Misra [2] investigated the dynamics of a cantilever beam being deployed in a dense incompressible fluid. Subsequently, Gosselin et al. [3] proved that the fluid-dynamic forces were not correctly accounted for in the analysis performed by Taleb and Misra [2]. Gosselin et al. [3] introduced an "axially added mass coefficient", which was proved to better approximate the force of the surrounding fluid acting on the beam. Recently, Wang and Ni [25] presented numerical results for the natural frequency for a supported axially moving beam in fluid based on the differential quadrature method. However, the axially moving systems presented in [2,3,25] belong to the first types of axially moving systems. In other words, the supports of the axially moving systems investigated in [2,3,25] were fixed and unmovable. In the case of the second types of axially moving systems surrounded by fluid, there are many engineering examples, such as slender structures towed underwater to the desired location [26] and the probe and drogue aerial refueling [27]. In the first stage of aerial refueling process (i.e. before the probe and drogue connected), a probe attached to the receiving aircraft can be modeled as a cantilever beam attached to an axially moving base immersed in fluid. Once connected, both aircraft continue to fly in formation until the fuel transfer is complete. The last stage of the aerial refueling is that when refueling is finished, the receiving aircraft slows down to disconnect the probe from the drogue basket. To the authors′ knowledge, the dynamics of an axially moving system subjected to axially moving support (i.e. the second types of axially moving systems) with consideration of fluid–structure interactions have not been reported yet. Motivated by this, we will investigate the dynamics of the cantilever beam attached to an axially moving base immersed in fluid.

The progress of the present study is described as follows. First, the equation of motions of the cantilever beam attached to an axially moving base immersed fluid will be derived. Second, the discrete equation of motion is obtained by the Galerkin method. Third, the effects of axially moving speed of base, mass ratio, and several other system parameters on the free vibration and stability are analyzed by calculating the natural frequencies and the lowest critical moving speed.

2. Problem formulation

The system to be analyzed, shown in Fig. 1, consists of a cantilever beam attached to an axially moving base with a known motion $L(t)$. Let this beam be of diameter D, with length l, area moment of inertia I, mass per unit length m and modulus of elasticity E. Consider this system to be immersed in an incompressible fluid of density ρ, with boundaries sufficiently distant to have negligible effect on the fluid forces on the beam. Only small lateral motions are considered in the present study. It is assumed that no separation occurs in the cross-flow around the beam, and that the forces of the fluid acting on a beam element are the same as those acting on a corresponding element of a long undeformed beam of the same cross-sectional area and inclination.

It is noted that the base of this cantilever beam undergoes an axial movement. In other words, the axial motion of this axially moving system is induced by the movement of the base. The transverse displacement of the base is constrained to zero, just like a conventional cantilever beam. However, the axial displacement of the base of the system shown in Fig. 1 is not constrained to zero but varied as times go by. Thus, two coordinate systems are introduced in this problem, namely, the absolute coordinate frame (x, z) fixed in a certain spatial point (i.e. o) and the moving coordinate $(\bar{x}, \bar{z})$ fixed in the base. The equation of motions will be derived in the absolute coordinate firstly. Then, the transformation of coordinates between the absolute and moving coordinates will be given, so that the boundaries of the beam become fixed and the equations of motion in the moving coordinate will be obtained by the transformation.

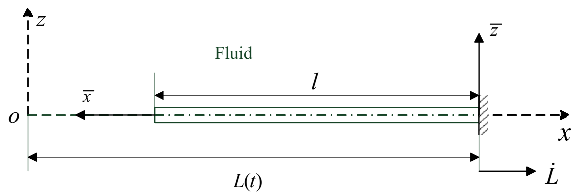

Fig. 1. The cantilever beam attached to an axially moving base immersed in fluid.