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Active vibration control of a flexible rod moving in water: Application to nuclear refueling machines[☆]

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ABSTRACT

This paper addresses a simultaneous control of the positions of the bridge and trolley and the vibrations of the load of a nuclear refueling machine (RM) that transports nuclear fuel rods to given locations in the nuclear reactor. Hamilton's principle is used to develop the equations of motion of the RM. The lateral and transverse vibrations of the fuel rods during their transportation in water are analyzed. In deriving the control law, the nonlinear hydrodynamic forces acting on the rod are considered. Then, a boundary control scheme is developed, which suppresses the lateral and transverse vibrations simultaneously in the course of the transportation of the fuel rod to the desired locations. Furthermore, Lyapunov function-based stability analyses are performed to prove the uniform ultimate boundedness of the closed loop system as well as the simultaneous control of the positions of the bridge and trolley under the influence of nonlinear hydrodynamic forces. Finally, experimental and simulation results are provided to demonstrate the effectiveness of the proposed control scheme.

1. Introduction

The refueling machine (RM) in Fig. 1 is a type of overhead crane that transports nuclear fuel rods to the desired locations in the reactor of a nuclear power plant. This paper discusses a simultaneous control problem of the positions of the trolley and the bridge of the RM and the residual vibrations of the fuel rod at its target position. The main difference of the RM from ordinary cranes is that it should carry the fuel rods in water to minimize possible radiation leaks from the fuel rods to the environment. During the transference of a fuel rod, the rod is subjected to vortex-induced forces as well as the drag forces caused by the movements of the RM. Consequently, these hydrodynamic forces affect the lateral and transverse deflections of the rod. If a rod undergoes a certain level of deflection, it can damage the fissile material inside the rod. Certainly, the insertion of a damaged fuel rod into a reactor core incurs a very serious safety hazard (Kim, 2010). Therefore, it is absolutely necessary to suppress unnecessary vibrations of the rod to ensure the reactor's safety. The main objective of this paper is to develop a simultaneous control strategy for moving a fuel rod to its desired location in water so that the suppression of the lateral and transverse vibrations is achieved at its target position.

The works on the control of nuclear fuel rods under the influence of hydrodynamic forces are rare in the literature. Also, the existing works discussed only the dynamics of the rod upon the coolant flow (axial flow) after core-insertion (Chen, 1975; Pavlica & Marshall, 1966). The present paper scrutinizes the dynamic response of the fuel rod against the cross flow in the course of its transportation. Recently, the authors have developed an underwater command shaping method for the suppression of the lateral vibrations of the rod generated by the movements of the RM (Shah, Hong, & Choi, 2017). The developed method there was successful when the vortex-induced vibration of the rod was small. However, it cannot be used when the speed of the RM becomes high. This is because the vortex-induced forces become high when the rod speed becomes high, and it causes the rod to vibrate in the transverse direction, besides its lateral vibrations. In this paper, a more realistic control model including the vortex-induced hydrodynamic forces in the reactor as well as the inline forces is to be developed, and a new control law that suppresses the transverse vibrations as well as the lateral vibrations of the rod in the presence of hydrodynamic forces will be developed.

The control problems of flexible systems in air have been extensively studied over the past decades (Bialy, Chakraborty, Cekic, & Dixon, 2016; Canciello & Cavallo, 2017; Hong & Bentsman, 1994; Nguyen & Hong, 2012b). Particularly, the control problem of a flexible inverted pendulum on a moving cart in air is closely related

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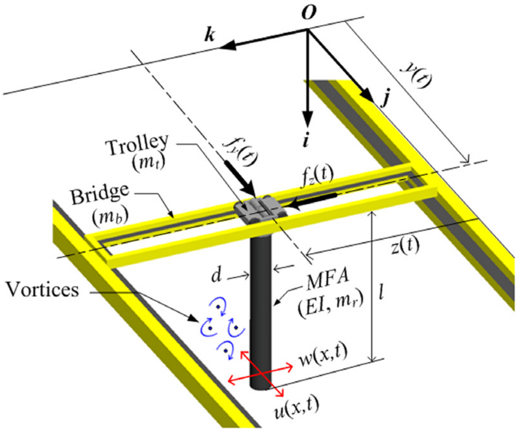

Fig. 1. 3D schematic of the refueling machine (MFA denotes the master fuel assembly).

to the control problem of an overhead crane in air (Lin & Chao, 2009; Park, Chung, Youm, & Lee, 2000). In comparison to the control problem in air, the dynamics of an object in water are more complicated. The effects of added mass, buoyancy force, viscous damping force, nonlinear drag force, vortex shedding, etc. need to be additionally considered. Several researchers have investigated the dynamics of flexible beams and cylinders in fluids, specifically in water (Han & Xu, 1996; Troesch & Kim, 1991). In particular, the vortex shedding phenomenon has received a significant attention: Vortex shedding denotes the oscillating flow existing behind the body in fluid, which is related to the transverse force (also called the lift force, but the word "lift" is reserved for the lifting motion of a crane) resulting in the transverse vibration (i.e., the vortex-induced vibration) of the rod (Williamson & Govardhan, 2004). Several experimental (Baarholm, Larsen, & Lie, 2006; Marcollo & Hinwood, 2006) and theoretical (Lie & Kaasen, 2006; Willden & Graham, 2001) results on the vortex-induced vibration have been reported with the aim of providing a realistic model for the transverse force (Facchinetti, de Langre, & Biolley, 2004; Marzouk, Nayfeh, Akhtar, & Arafat, 2007).

Also, the dynamics of deep-sea oil exploration systems were discussed in relation to the hydrodynamic forces acting along the length of a beam (Furnes, 2000; He, Ge, How, Choo, & Hong, 2011; How, Ge, & Choo, 2009). In their formulation, one end was assumed fixed to the seabed and the other, assuming a tip mass, was free (i.e., a vessel to which the riser was attached). In these studies, only the control of the beam itself was considered (not the vessel). However, the present paper considers a hybrid model of the RM system consisting of two lumped masses (i.e., the bridge and the trolley) and a flexible master fuel assembly (one end of the flexible beam is affixed to the RM and the other is free), which vibrates in the lateral and transverse directions when the RM moves. Several control techniques applicable to under-actuated mechanical systems have been reported in the literature (Gao, Lam, & Wang, 2006; Gao, Sun & Shi, 2010; He & Ge, 2016; Hong, Sohn, & Hedrick, 2002; Li, Yan, & Shi, 2017; Liberzon, Nesic, & Teel, 2014; Ngo & Hong, 2012a, b; Parisini & Zoppoli, 1994; Park, Chwa, & Hong, 2007; Pin & Parisini, 2011; Shah & Hong, 2014; Teel, Forni, & Zaccarian, 2013; Zhao, Liu, Guo, & Fu, 2017).

The research objective of this paper is to control both the rigid body motions of the RM and the lateral and transverse vibrations of the flexible rod. One way of achieving the suppression of the flexible rod's vibrations is to implement a distributed control, which requires the mounting of several actuators and sensors along the length of the rod. Since such distributed control is designed based on a finite number of system modes, it suffers from the spillover problem caused by the actuation of unmodeled modes and, eventually, therefrom, instability (Meirovitch & Baruh, 1983). Therefore, to avoid such situation, the present paper pursues a more easily implementable boundary control technique that requires actuation and sensing only at the boundaries (Choi, Hong, & Yang, 2004; Nguyen & Hong, 2010; Yang, Hong, & Matsuno, 2004, 2005a, b). For hybrid rigid and flexible systems, several boundary control schemes have been reported in the literature (Esterhuizen & Levine, 2016; Hasan, Aamo, & Krstic, 2016). Lotfazar, Eghtesad, and Najafi (2008) reported a boundary control scheme for simultaneous control of the lateral vibration and trajectory tracking of an Euler–Bernoulli beam. However, their control model did not include the actuator's dynamics. Nguyen and Hong (2012a) presented a boundary control scheme for suppressing the longitudinal and transverse vibrations of an axially moving string while achieving velocity tracking. He and Ge (2015) then reported a boundary control scheme for suppressing the vibrations of two flexible solar panels attached to a satellite (rigid body). Later, He and Zhang (2017) developed a boundary control scheme to suppress the twist and bending phenomena in the flexible wing system of a robotic aircraft. Recently, a neural network based adaptive control strategy was proposed to suppress the vibrations of a flexible robotic manipulator in consideration of input dead-zone nonlinearity (He, Ouyang, & Hong, 2017). However, all these studies addressed control problems for systems operating in air.

As for the system operating in water, such control problems of marine risers and mooring systems are more relevant to the present work. Several boundary control schemes for the suppression of the lateral vibrations of a riser system, which utilize actuation and sensing at the top boundary of the riser through the movement of the vessel, have been proposed (Do & Pan, 2008; He et al., 2011; Nguyen, Do, & Pan, 2013). The riser control problem however is limited to the vibration suppression of the riser only (i.e., the position control of the vessel was not considered). However, it is important to restrain the vessel's movement to avoid any possible damage to the mooring lines. In the work of He, Zhang, and Ge (2014), a thruster-assisted robust adaptive boundary control scheme was proposed to limit the vessel's movement. Considering all these works, the following challenge for our control problem is stated: Suppression of the lateral and transverse vibrations of the rod in the course of the movement of the RM in pursuit of its target position and in the presence of nonlinear hydrodynamic forces.

The contributions of this paper are the following: First, a hybrid model of the RM (consisting of two lumped masses representing the bridge and the trolley and one flexible system representing the master fuel assembly affixed to the RM) is newly developed. Hamilton's principle is utilized in obtaining the equations of motion of the coupled system, where both movements of trolley and bridge inflict the lateral and transverse vibrations of the rod under the effect of inline and transverse forces. The hydrodynamic forces appear as nonlinear functions of the velocities of the RM and the rod. Second, a boundary control scheme for the simultaneous suppression of the lateral and transverse vibrations of the rod and the position control of the RM is designed using the Lyapunov method. The overall control scheme consists of two control laws: One for the trolley and the other for the bridge. When the RM is sent to a target position with the developed control laws, the lateral and transverse vibrations of the rod are shown satisfactorily suppressed in both simulation and experiment. Third, the proposed control scheme guarantees the uniform ultimate boundedness of the closed-loop system from the sense that the position errors of the bridge and the trolley go to zero when the fluid-induced forces in the nuclear reactor go to zero.