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Brief paper

Modeling and vibration control of a flexible aerial refueling hose with variable lengths and input constraint[☆]

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ABSTRACT

In this paper, we present boundary control design for a flexible aerial refueling hose with varying length, varying speed, and input constraint. By the extended Hamilton's principle, the flexible hose is modeled as a distributed parameter system described by partial differential equations (PDEs). Then a boundary control scheme is proposed based on the original PDEs to regulate the hose's vibration and handle the effect of the input constraint. It is shown that the state of the system is proven to converge to a small neighborhood of zero in the presence of the varying length, varying speed and input constraint. The results are illustrated using numerical simulations for control performance verification.

1. Introduction

Autonomous aerial refueling (AAR) has been an active topic, and significant research has been carried out and in process for the detection, control and guidance of the tanker and the receiver (Ro, Kuk, & Kamman, 2010; Williams & Trivailo, 2007; Zhu & Meguid, 2007), spurred by a rapid integration of unmanned aerial vehicles (UAVs) into modern military missions. A hose–drogue aerial refueling system depicted in Fig. 1 consists of a flexible hose and an active drogue control actuator, which are the most universal refueling equipments of probe–drogue refueling (PDR). The probe and drogue systems are comparatively simpler and more compact than the flying boom, and their arrangement on the tanker enables multiple aircraft to be refueled simultaneously. The significant drawback is that PDR requires a skillful piloting technique of maneuvering a probe into the center of a moving drogue with an acceptable closure rate. Due to the flexible property of the hose, the deflection of the flexible hose has a significant influence on the dynamics and control performance of the AAR. In addition, the excess vibrations will lead to premature fatigue failure, and limits the utility of the systems. Therefore, the vibration suppression is a vital research relevant to a flexible aerial refueling hose. The idea of a controllable drogue has been developed much recently, where Kuk, Ro, and Kamman (2011) and Ro et al. (2010) present simulations and wind tunnel tests of a controllable drogue. An approach is proposed in Williamson et al. (2010) involving manipulation of the drogue canopy in a manner to alter the aerodynamic forces. In Williams, Sgarioto, and Trivailo (2006), the optimal control of an aerial-towed flexible cable system is proposed to account for the bowing of the cable. The control design for a previously developed aerial refueling hose–drogue system during receiver–probe coupling is studied in Ro, Kuk, and Kamman (2011). In Wang, Dong, Xue, and Liu (2014), a dynamic model of the variable-length hose–drogue aerial refueling system (HDRS) is built and an integral sliding mode back-stepping controller is proposed for the whipping phenomenon. The researches previously mentioned relate to two types of modeling approaches, which are the elasto-dynamic hose model based on the finite element method (FEM), and the lumped mass hose model with rigid link kinematics. However, the two approaches based on truncated models can cause spillover effects, which result in instability when the control of the system is restricted to a few critical modes (Meirovitch & Baruh, 1983). To avoid these problems, the flexible hose is regarded as a distributed parameter system which is infinite dimensional and described by partial differential equations (PDEs). Moreover, the control design in

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above papers do not consider the changing length of the hose. These problems add some challenges for the control design.

The control design and stability analysis of flexible mechanical systems based on PDEs has been extensively studied and made significant progress (Guo & Jin, 2014; He & Ge, 2015, 2016; He, He, & Ge, 2016; Hong, 1997; Krstic, Guo, Balogh, & Smyshlyaev, 2008; Liu, Liu, & He, 2015; Smyshlyaev, Guo, & Krstic, 2009; Wu, Zhu, & Wang, 2015; Zhang, He, & Huang, 2016). Modeling and control of moving systems have typically been studied (Li & Rahn, 2000; Zhu & Ni, 2000; Zhu, Ni, & Huang, 2001). In Qu (2002), boundary control schemes are proposed to reduce the vibrations of a stretched moving string, where an iterative learning algorithm is used to deal with the effects of the external boundary disturbance. In Nguyen and Hong (2012a) an active control scheme for an axially moving string system that suppresses both longitudinal and transverse vibrations and regulates the transport velocity of the string to track a desired moving velocity profile is investigated. In Nguyen and Hong (2012b), a novel control algorithm is discussed for an axially moving membrane system to regulate the transverse vibrations and track a desired axial transport velocity. In He, Ge, and Huang (2015), boundary control laws are developed to stabilize the transverse vibration for a nonlinear vertically moving string system which is considered with varying length, varying speed, and the constrained boundary output. The above works mainly deal with the problems for moving systems with a horizontal or a vertical speed, however, the flexible aerial refueling hose system has both horizontal and vertical speeds.

In many practical systems, physical input constraint on hardware dictates that the magnitude of the control signal is always constrained (Chen, Ge, & Ren, 2011; Gao & Selmic, 2006; Wen, Zhou, Liu, & Su, 2011). The saturation often degrades the performance of the control system or leads to the instability if they are ignored in the control design. Therefore, the problem for the saturation constraints is a topic of great importance, and many methods to solve this problem are proposed. In Gao and Selmic (2006), a neural net based actuator saturation compensation scheme for the nonlinear systems in Brunovsky canonical form is presented, where the actuator saturation is assumed to be known and the saturation compensator is inserted into a feed-forward path. A simple controller with smooth hyperbolic function for achieving trajectory tracking under the condition of restricted input is presented in Ailon (2010). In Chen et al. (2011), an adaptive tracking control scheme is proposed for a class of uncertain multi-input and multi-output nonlinear systems with non-symmetric input constraints, where the auxiliary design system is introduced to analyze the effect of input constraints, and its states are used to adaptive tracking control design. In Wen et al. (2011), a robust adaptive controller is designed for uncertain nonlinear systems with input saturation and external disturbances by using a Nussbaum function. However, all the above mentioned works about input constraints investigate the control problem for the ODE systems with input saturation.

In this paper, we present boundary control design for a flexible aerial refueling hose with varying length, horizontal and vertical speeds, and input constraint. The flexible hose is described by PDEs. With the backstepping technology, a novel boundary controller is proposed for the flexible hose based on PDEs. With the proposed control, the closed-loop stability is proved based on the Lyapunov's direct method and the deflection eventually converges to an arbitrarily small neighborhood around the origin. The main contributions of this paper are that: (1) a boundary control scheme with a smooth hyperbolic function is proposed to suppress the vibration of the flexible hose subject to varying length, varying speed, and input constraint, (2) an auxiliary system is designed to compensate for the nonlinear term arising from the input saturation, and (3) the close-loop stability analysis avoids any simplification or discretization of the PDEs based on the Lyapunov's method.

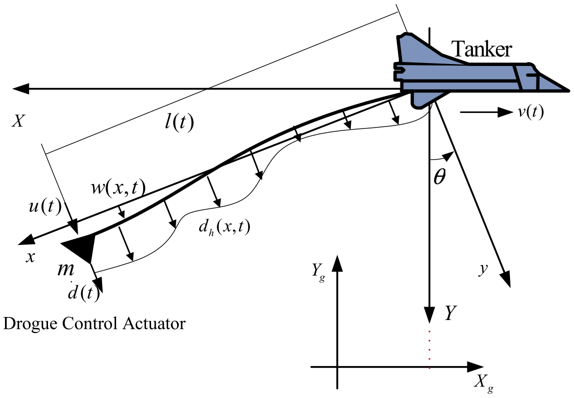

Fig. 1. Diagram of a flexible aerial refueling hose.

The rest of the paper is organized as follows. The PDE dynamic model of a flexible aerial refueling hose is derived in Section 2. In Section 3, a boundary control scheme is designed. In Section 4, the closed-loop stability is proved based on the Lyapunov's direct method. Numerical simulations are demonstrated in Section 5 to show the effectiveness of the proposed controller. A conclusion is drawn in Section 6.

2. Problem statement

As shown in Fig. 1, $X_g - Y_g$ represents an inertial reference coordinate system. $X - Y$ represents the local coordinate system which is attached to and moves with the tanker, and $x - y$ represents the body-fixed coordinate system attached to the hose. In this paper, we consider the transverse degree of freedom only. The orientation of the hose with respect to the local horizontal is denoted by θ. The control $u(t)$ is implemented by a drogue control actuator, $w(x, t)$ is the elastic deflection of the hose with respect to the frame $x - y$ at the position x for time t. The tanker has the speed $v(t)$ relative to $X_g - Y_g$ and its position vector relative to the frame $X_g - Y_g$ is $\begin{pmatrix} r(t), & h_0 \end{pmatrix}^T$. The position vector of the hose $p(x, t)$ respective to the frame $X - Y$ at the position x for time t is described by

$$p(x,t) = \begin{pmatrix} p_x(x,t) \\ p_y(x,t) \end{pmatrix} = \begin{pmatrix} x\cos\theta - w(x,t)\sin\theta \\ x\sin\theta + w(x,t)\cos\theta \end{pmatrix}.$$

The absolute position vector of a point along the hose respective to the frame $X_g - Y_g$ is denoted by

$$z(x,t) = \begin{pmatrix} z_x(x,t) \\ z_y(x,t) \end{pmatrix} = \begin{pmatrix} r(t) - p_x(x,t) \\ h_0 - p_y(x,t) \end{pmatrix}.$$

2.1. Dynamic analysis

In this paper, the dynamical model of the tanker is not considered, and the tanker provides the same speed for the undeformed hose.

The kinetic energy of the hose system including the drogue $E_k(t)$ can be represented as

$$E_k(t) = \frac{\rho}{2}\int_0^{l(t)} \left\{ \left(\frac{Dz_x(x,t)}{Dt}\right)^2 + \left(\frac{Dz_y(x,t)}{Dt}\right)^2 \right\} dx + \frac{1}{2}m\left\{ \left(\frac{Dz_x(l(t),t)}{Dt}\right)^2 + \left(\frac{Dz_y(l(t),t)}{Dt}\right)^2 \right\} \tag{1}$$