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Dynamic modeling and vibration control of a flexible aerial refueling hose

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ABSTRACT

In this study, we consider a boundary control problem of a flexible aerial refueling hose in the presence of input disturbance. To provide an accurate and concise representation of the hose's behavior, the flexible hose is modeled as a distributed parameter system described by partial differential equations (PDEs). Boundary control is proposed based on the original PDE dynamics to regulate the hose's vibration. A disturbance observer is designed to estimate the input disturbance. Then based on Lyapunov's direct method, the state of the system is proven to converge to a small neighborhood of zero by appropriately choosing design parameters. Finally, the results are illustrated using numerical simulations for control performance verification.

1. Introduction

As the number of unmanned aerial vehicles (UAVs) increases in modern military missions, autonomous aerial refueling (AAR) has gained substantial attention, and significant research is carried out and in process for the detection, control and guidance of the tanker and the receiver [1–5]. A hose-drogue aerial refueling system consists of a flexible hose-drogue on a tanker and a probe on a receiver, which is the most universal refueling equipment because of its various advantages such as simple and cheap tanker, multipoint hose-drogue, and no boom operator. However, 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. Therefore, the vibration suppression is a vital research relevant to a flexible aerial refueling hose. In [6], 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. In [7], 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 [8]. These works 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 [9]. The control order needs to be increased with the number of flexible modes considered to obtain high accuracy of performance. 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), however, it adds unique challenges for the control design.

The control design and stability analysis of flexible mechanical systems based on PDEs has been extensively studied [10–15]. The asymptotic behavior of a partial state of a coupled PDE and ordinary differential equation (ODE) is investigated in [16]. A robust adaptive boundary controller for a flexible marine riser with vessel dynamics is developed to suppress the riser's vibration in [16]. In [17], a boundary output feedback controller is designed for a one-dimensional Euler–Bernoulli beam with general external disturbance based on PDEs. In [18], vibration control of a flexible satellite modeled as two Euler–Bernoulli beams is proposed. In [19], boundary control laws are developed to stabilize the transverse vibration for a nonlinear vertically moving string system in the presence of boundary output constraints. However, the model of a flexible hose is different from that in the paper mentioned above. A flexible aerial refueling hose system needs consider the horizontal velocity and gravity. Different from the axially moving string in [19], the hose moves horizontally at an angle, which makes the control problem in this paper more difficult to handle compared to the previous works.

In this paper, we investigate the boundary control problem for a flexible aerial refueling hose. The refueling process begins with

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Nomenclature

L	Length of the hose	$v(t)$	Speed of the tanker relative to $X_g - Y_g$
m	Mass of the actuator	$u(t)$	Control input imposed on the top of the hose
g	Acceleration of gravity	$d(t)$	Boundary disturbance on the actuator
ρ	The density of the hose	$P(x,t)$	Tension of the hose
D	The diameter of the hose	$w(x,t)$	Deflection with respective to the frame x–y at the position x for time t
θ	Orientation of the hose with respect to the local horizontal		

the tanker deploying the hose. Assuming that the tanker flies horizontally and considering the aerodynamic forces and the gravity of the hose, the hose will be angled to the local horizontal. When the end of hose couples with the receiver, it starts refueling. Due to the huge strains of the hose while refueling, vibration of the hose can produce premature fatigue problems. Therefore, we propose boundary control to suppress the vibration of the hose described by PDEs. With the proposed control, the closed-loop stability is proved based on the Lyapunov's direct method.

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 and analyzed. Numerical simulations are demonstrated in Section 4 to show the effectiveness of the proposed controller. A conclusion is drawn in Section 5.

2. Problem statement

A typical aerial refueling hose system in Fig. 1 is the connection between a tanker and a receiver aircraft. 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 horizontally with the receiver aircraft, and x–y the body-fixed coordinate system attached to point of junction between the hose and the receiver aircraft. In this paper, we consider the transverse degree of freedom only. The orientation of the hose without deflections with respect to the local horizontal is denoted by θ. The control $u(t)$ is implemented from the actuator in the tanker, that is the top boundary of the hose. The tanker and the receiver aircraft have the same speed $v(t)$ with relative to $X_g - Y_g$. The receiver aircraft is at the position $r(t)$ relative to $X_g - Y_g$. $w(x,t)$ is the elastic deflection with respective to the frame x–y at the position x for time t, and 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 is denoted by

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

2.1. Dynamic analysis

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

$$E_k(t) = \frac{\rho}{2}\int_0^L \left(\dot{z}_x^2(x,t) + \dot{z}_y^2(x,t)\right)dx + \frac{1}{2}m\left(\dot{z}_x^2(L,t) + \dot{z}_y^2(L,t)\right) \quad (1)$$

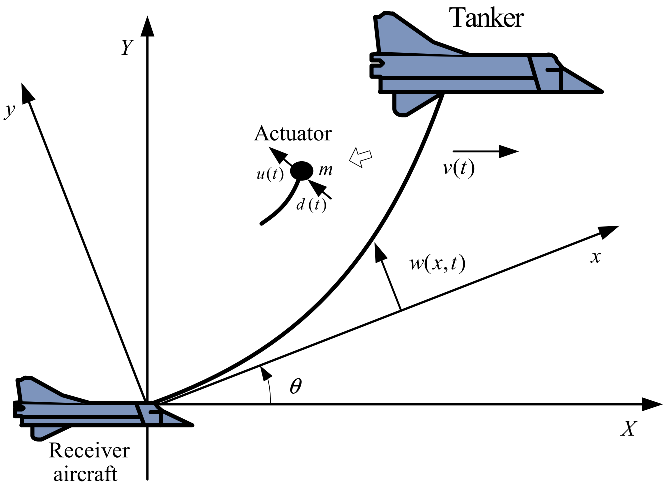

Fig. 1. Diagram of a flexible aerial refueling hose.

The potential energy of the hose system $E_p(t)$ due to the axial force can be obtained from

$$E_p(t) = \frac{1}{2}\int_0^L P(x,t)\left[w'(x,t)\right]^2 dx \quad (2)$$

where $P(x,t)$ is the tension of the hose that can be expressed as [20]

$$P(x,t) = f_t(x,t) + \rho x(g\sin\theta + \ddot{r}(t)\cos\theta) \quad (3)$$

where g is the acceleration of gravity, and ρ is the density of the hose. $f_t(x,t)$ is the skin friction drag in the tangential direction. The virtual work done on the system is given by

$$\delta W(t) = -\int_0^L f_n(x,t)\delta w(x,t)\,dx + \int_0^L \rho g\cos\theta\,\delta w(x,t)dx + (u(t) + d(t))\,\delta w(L,t) \quad (4)$$

Then, the Hamilton's principle is applied as

$$\int_{t_1}^{t_2} (\delta E_k(t) - \delta E_p(t) + \delta W(t))dt = 0 \quad (5)$$

where $\delta(\cdot)$ represents the variation of $(\cdot)$. We further obtain the following PDEs of the hose system as

$$\rho\ddot{w}(x,t) = P'(x,t)w'(x,t) + P(x,t)w''(x,t) + Q(x,t) \quad (6)$$

$$Q(x,t) = -f_n(x,t) + \rho\,(g\cos\theta + \ddot{r}(t)\sin\theta) \quad (7)$$

and boundary conditions of the hose system as

$$m\ddot{w}(L,t) - m\ddot{r}(t)sin\theta + P(L,t)w'(L,t) - u(t) - d(t) = 0 \quad (8)$$

$$w(0,t) = \dot{w}(0,t) = 0 \quad (9)$$