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Research Article

Robust Control for the Suspension Cable System of the Unmanned Helicopter with Sensor Fault under Complex Environment

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Aiming at the suspension cable system of an unmanned helicopter with sensor fault under complex environment, this paper studies the robust antiswing tolerant control scheme. To suppress the swing of the hanging load when the unmanned helicopter is in the forward flight state, a nonlinear line motion model is firstly established. Considering the sensor fault of the unmanned helicopter, a sensor fault estimator is developed. By using the fault estimator output, the robust antiswing tolerant controller is proposed using the backstepping technique and sliding mode control method. Under the designed robust antiswing tolerant controller, the desired tracking control performance can be obtained and the swing angle of the load is guaranteed small under the sensor fault. Furthermore, the closed-loop system stability is analyzed by using the Lyapunov technique. Simulation studies are given to show the efficiency of the designed robust antiswing control strategy.

1. Introduction

Due to the unique characteristics such as vertical takeoff, vertical landing, good maneuverability, high work capability in complex environments, and hovering low-speed flying, the helicopter has been widely used in different practical areas during the past several decades [1]. Specially, considering the superiorities of long flight distance, high altitude, strong robustness, and large load, the medium-scale helicopter receives great attention [2]. By using the ability of long flight distance and large load of medium-scale helicopter, we can carry out the external transport by using the suspension cable, which is one of the main applications of medium-scale helicopters in the military and civil application area [3]. Suspension flight can transport bulk goods, which does not need to consider the load capacity of helicopters and appearance of the goods. Compared with the helicopter free flying state, helicopter flight with additional load will increase the load gravity load and load disturbance. Thus, it is necessary to consider the influence of the hanging load on the system. The characteristics of the low-speed stability were analyzed for a helicopter with a sling load in [4]. In [5], the flight dynamics were established for the articulated rotor helicopter by considering an hanging load.

Because the working environment is complicated and dynamically changeable, it is a challengeable task to develop a good control law for a helicopter suspension cable system [6–8]; for example, the medium-scale helicopter can be used to monitor and suppress the forest fire. However, the complex and changeable forest environment will increase the probability of a crash for the medium-scale helicopter. To avoid human sacrifice in the work process, the suspension cable system of an unmanned helicopter is developed in recent years. In [9], to deliver airborne cargo precisely, an active control scheme was designed for an unmanned helicopter with a slung load. An antiswing controller was designed for the unmanned helicopter with slung load by nonlinear path tracking in [10]. In [11], an adaptation controller was developed for autonomous helicopter slung load operations. A nonlinear controller design was developed for a helicopter slung load system in [12]. In [13], an adaptation backstepping controller by using prescribed performance method was proposed for carrier used unmanned aerial vehicle. Furthermore, in order to improve the security and the economic efficiency, the efficient controller should be further designed for the suspension cable system of an unmanned helicopter with sensor fault.

Sensor fault is an important fault of the practical systems due to the external circuit fault and mechanical fault of sensor and so on [14–18]. In general, there are four main types of sensor faults which include the complete failure fault, the fixed deviation fault, the drift deviation fault, and the precision reduction fault [19]. Now, there are many research results for the tolerant control problem of the various system with faults and unknown disturbance [20–27]. In [28], the local stabilization was studied for the Takagi–Sugeno (T-S) fuzzy discrete-time time-delay system in the presence of sensor fault. The sensor fault diagnosis technique and fault-tolerant control methods were developed for stochastic time-delayed control systems in [29]. In [30], the observer design method of the fault estimation was given for descriptor switched systems with sensor and actuator faults. The robust sensor fault estimator was studied for the continuous interconnected system in [31]. In [32], the tolerant control strategy was designed for an autonomous vehicle with proprioceptive sensors' fault. A fault-tolerant control was developed for the linear system with sensor and actuator faults by using observer-based $\mathscr{H}_\infty$ method in [33]. However, the fault-tolerant control methods need further development to improve their safety of various aircrafts with sensor fault.

In the past several years, various tolerant control schemes of the aircrafts with sensor fault have been studied [34]. In [35], the detection and recovery method was studied for the satellite attitude control system with sensor fault. Aiming at the hypersonic flight vehicle with multisensor faults, a nonlinear fault-tolerant control scheme was developed in [36]. In [37], an observer-based tolerant control scheme was designed for unmanned aerial vehicle with sensor faults. The reconstruction method was proposed for the aircraft with sensor fault under disturbances in [38]. In [39], the estimation method was studied for flight control systems with sensor fault based on the identification of aerodynamic parameters. In [40], a fuzzy adaptive tolerant control scheme was proposed for a quadrotor unmanned aerial vehicle with nonlinear sensor fault. However, the fault-tolerant control methods are rare for the suspension cable system of an unmanned helicopter with sensor fault which needs to be further studied.

Motivated by above analysis, the scheme of a robust antiswing control is studied for the suspension cable system of an unmanned helicopter with sensor fault to improve its reliability. The key innovations of this paper are stated as follows:

(1) A design method of estimator is proposed to solve the estimation problem of sensor fault in suspension cable system of an unmanned helicopter.

(2) The robust antiswing control law is developed for the suspension cable system of an unmanned helicopter by using sensor fault estimator, backstepping technology, and the desired tracking trajectory.

(3) The closed-loop system stability of an unmanned helicopter with sensor faults is strictly analyzed under the robust antiswing control scheme.

The organization of this paper is described as follows. Section 2 gives the problem description, and the system model is introduced. The sensor fault estimator is proposed for the antiswing control in Section 3. Section 4 designs the robust antiswing control scheme based on sensor fault estimator. In Section 5, simulation results and analysis are given to show the effectiveness of the studied antiswing control scheme, and some conclusions are drawn in Section 6.

2. Problem Description

In this paper, the load uses a single-point hanging method to connect with the unmanned helicopter, which is the most widely used one because of compact and simple structure. To simplify the design of the controller, only the linear motion of the suspension cable system of the unmanned helicopter suspension system is considered, as shown in Figure 1 [3].

To establish the line motion model of the suspension cable system of an unmanned helicopter, we assume that the load swing amplitude at the initial time is zero; the unmanned helicopter sling is assumed to be massless, always straightened during flight, and will not come loose; the distance between the sling point and the unmanned helicopter particle is ignored; unmanned helicopter and hanging object are rigid bodies, without considering elastic deformation, and the load is regarded as a particle without considering the shape of the load. Ignore the influence of rotor airflow on unmanned helicopter and load movement and ignore the external disturbances, such as the wind, during the movement [3].

Under above assumptions, by using the Lagrange method, the nonlinear line motion model of the suspension cable system of an unmanned helicopter can be described as follows [3]:

$$\begin{cases} \ddot{x} = \dfrac{m_l \sin\theta\left(L\dot{\theta}^2 + g\cos\theta\right) + T}{M_h + m_l \sin^2\theta}, \ddot{\theta} = \dfrac{-(M_h + m_l)g\sin\theta - m_l L\dot{\theta}^2 \sin\theta\cos\theta - T\cos\theta}{L\left(M_h + m_l \sin^2\theta\right)}, \end{cases} \tag{1}$$

where T is the lift of unmanned helicopter which is the control input. x is the unmanned helicopter displacement, and θ is the swing angle of hanging load which are system outputs. M_h is the unmanned helicopter mass, m_l is the

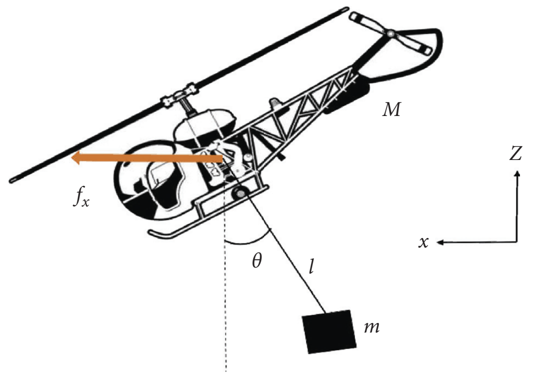

FIGURE 1: The straight line motion of the suspension cable system of the unmanned helicopter with single point hanging.

suspension load mass, g is the gravity acceleration, and L is the length of suspension cable.

Define $X = [cx_1\ x_2\ x_3\ x_4]^T = [cx\ \theta\ \dot{x}\ \dot{\theta}]^T$ and $u = T$. Then, system (1) can be expressed as

$$\begin{cases} \dot{x}_1 = x_3, \\ \dot{x}_2 = x_4, \\ \dot{x}_3 = f_1(X) + g_1(X)u, \\ \dot{x}_4 = f_2(X) + g_2(X)u, \end{cases} \quad (2)$$

where x_1 denotes the helicopter displacement x, x_2 is the swing angle of hanging load θ, x_3 is the forward flight speed of helicopter $\dot{x}$, x_4 denotes the angular velocity $\dot{\theta}$ of the swing angle of hanging load θ, and u is the lift T. $f_1(X)$, $g_1(X)$, $f_2(X)$, and $g_2(X)$ are given by

$$\begin{aligned} f_1(X) &= \frac{m_l \sin\theta\left(L\dot{\theta}^2 + g\cos\theta\right)}{M_h + m_l \sin^2\theta}, \\ g_1(X) &= \frac{1}{M_h + m_l \sin^2\theta}, \\ f_2(X) &= \frac{-(M_h + m_l)g\sin\theta - m_l L\dot{\theta}^2 \sin\theta\cos\theta}{L\left(M_h + m_l\sin^2\theta\right)}, \\ g_2(X) &= \frac{-\cos\theta}{L\left(M_h + m_l\sin^2\theta\right)}. \end{aligned} \quad (3)$$

Define $X_1 = [x_1, x_2]^T$ and $X_2 = [x_3, x_4]^T$. Assume that the system output is y and $y = X_1$. Then, we have

$$\begin{cases} \dot{X}_1 = X_2, \\ \dot{X}_2 = F(X) + G(X)u, \\ y = X_1, \end{cases} \quad (4)$$

where $F(X) = [f_1(X), f_2(X)]^T$ and $G(X) = [g_1(X), g_2(X)]^T$.

In this paper, the forward speed $\dot{x}$ is measured by airspeed head and the swing angle of hanging load θ is surveyed using an optical camera. We assume that accuracy losses of the airspeed head sensor and the optical camera sensor are considered in this study. The loss of accuracy of two sensors is given as follows [40]:

$$\chi = X_2 + D(t), \quad \forall t \ge t_f, \quad (5)$$

where χ is the measured value of the airspeed head sensor and the optical camera sensor with fault $D(t)$ and t_f is the sensor fault occurring time.

The control design goal of this paper is to develop a robust antiswing control plan such that the system actual output y can track the required one y_c and the tracking error $e_1 = y - y_c$ is convergent when the suspension cable system of the unmanned helicopter (3) suffers from the sensor fault.

To promote the design of the robust antiswing control scheme for the suspension cable system of the unmanned helicopter with sensor fault, some assumptions and lemmas are required.

Assumption 1. (see [40]). For the sensor fault D, there exist corresponding inequality conditions $\|D\| \le \tau_0$, $\|\dot{D}\| \le \tau_1$, and $\|\ddot{D}\| \le \tau_2$ with $\tau_i > 0, i = 0, 1, 2$.

Assumption 2. (see [2]). All states of the studied system are measurable and available. The desired system tracking signal y_c and its derivative are always bounded. Furthermore, there exists an unknown positive constant Δ_0 which renders $C_0\colon = \left\{(y_c, \dot{y}_c, \ddot{y}_c)\colon \|y_c\|^2 + \|\dot{y}_c\|^2 + \|\ddot{y}_c\|^2 \le \Delta_0\right\}$.

Lemma 1. *(see [41]). For the any bounded initial conditions, if there is a C^1 positive and continuous Lyapunov function $V(x)$ which satisfies $\rho_1(\|x\|) \le V(x) \le \rho_2(\|x\|)$ and makes that $\dot{V}(x) \le -k_1 V(x) + k_2$, where $\rho_1, \rho_2\colon R^n \longrightarrow R$ are class K functions and k_1, k_2 are positive constants, then its solution $x(t)$ is uniformly bounded.*

Remark 1. In this paper, the sensor fault is considered for the suspension cable system of an unmanned helicopter. As well known, the sensor fault and its derivatives should be bounded in the practical system. If they are not bounded, the system controllability cannot be guaranteed. Thus, Assumption 1 is reasonable for the helicopter suspension cable system. On the other hand, to design the robust antiswing control law for the suspension cable system of an unmanned helicopter, all states are needed. Thus, we assume that all states are measurable and available. Furthermore, the desired system tracking signal y_c and its derivative are also bounded. If they are not bounded, the tracking control goal of the suspension cable system of an unmanned helicopter with sensor fault cannot be realized. From above analysis, we can conclude that Assumption 2 is also reasonable.

3. Design of Sensor Fault Estimator

In this section, the design of sensor fault estimator will be given for the suspension cable system of the unmanned helicopter. Considering (4) and (5), we have

$$\begin{aligned} \dot{\chi} &= \dot{X}_2 + \dot{D}(t) \\ &= F(X) + G(X)u + \dot{D}(t). \end{aligned} \quad (6)$$

Since $F(X)$ includes $\dot{\theta}$, $F(X)$ can be written as $F(X) = F(X_1, \chi) + \Delta F(X_2)$. At the same time, $G(X) = G(X_1)$. Thus, we obtain

$$\dot{\chi} = F(X_1, \chi) + \Delta F(X_2) + G(X_1)u + \dot{D}(t). \tag{7}$$

Without loss of generality, we assume $\Delta F(X_2)$ and its derivative are bounded. Then, $\|\Delta F(X_2)\| \le \tau_3$ with $\tau_3 > 0$. Because the uncertain term $\Delta F(X_2)$ is generated by the sensor fault, this assumption is reasonable. Under the sensor faults, the nonlinear line motion model (4) of the suspension cable system of an unmanned helicopter can be described as

$$\begin{cases} \dot{X}_1 = X_2, \\ \dot{\chi} = F(X_1, \chi) + G(X_1)u + \dot{D}(t) + \Delta F(X_2), \\ y = X_1. \end{cases} \tag{8}$$

Invoking (5), system (8) can be modified as

$$\begin{cases} \dot{X}_1 = \chi - D(t), \\ \dot{\chi} = F(X_1, \chi) + G(X_1)u + \dot{D}(t) + \Delta F(X_2), \\ y = X_1. \end{cases} \tag{9}$$

To estimate the unknown sensor fault of the suspension cable system of the unmanned helicopter, the sensor fault estimator can be designed as follows [41]:

$$\begin{aligned} \widehat{D} &= z_1 + L_1(X_1), \\ \dot{z}_1 &= -P_1(X_1)(\chi - \widehat{D}) + \widehat{\dot{D}}, \\ \dot{\widehat{D}} &= z_2 + L_2(\chi), \\ \dot{z}_2 &= -P_2(\chi)\Big(F(X_1, \chi) + G(X_1)u + \widehat{\dot{D}}\Big), \end{aligned} \tag{10}$$

where $\widehat{D}$ and $\widehat{\dot{D}}$ are the corresponding estimations of the sensor fault D and the derivation of the sensor fault $\dot{D}$. $L_1(X_1)$ and $L_2(\chi)$ are the parameters of the studied sensor fault estimator which needs to be designed. The parameters $P_1(X_1)$ and $P_2(\chi)$ should satisfy $P_1(X_1) = (\partial L_1(X_1)/\partial X_1)$ and $P_2(\chi) = (\partial L_2(\chi)/\partial \chi)$. z_1 and z_2 are the internal states of the fault estimator.

Define the estimation errors of the fault estimator as $\widetilde{D} = \widehat{D} - D$ and $\widetilde{\dot{D}} = \dot{D} - \widehat{\dot{D}}$. Then, considering (9) and (10), there yields

$$\begin{aligned} \dot{\widetilde{D}} &= \dot{D} - \dot{\widehat{D}} = \dot{D} - \dot{z}_1 - P_1(X_1)\dot{X}_1 \\ &= -P_1(X_1)\widetilde{D} + \widetilde{\dot{D}}, \end{aligned} \tag{11}$$

$$\begin{aligned} \dot{\widetilde{\dot{D}}} &= \ddot{D} - \dot{\widehat{\dot{D}}} = \ddot{D} - \dot{z}_2 - P_2(\chi)\dot{\chi} \\ &\quad - P_2(\chi)\widetilde{D} + \ddot{D} - P_2(\chi)\Delta F(X_2). \end{aligned} \tag{12}$$

We define $e_f = [\widetilde{D}^T, \widetilde{\dot{D}}^T]^T$. Invoking (11) and (12), we obtain

$$\dot{e}_f = Q(\overline{x})e_f + H_1\ddot{D} + H_2\Delta F(X_2), \tag{13}$$

where $\overline{x} = [X_1, \chi]$, $Q(\overline{x}) = \begin{bmatrix} -P_1(X_1) & I_2 \\ -P_2(\chi) & 0 \end{bmatrix}$, $H_1 = \begin{bmatrix} 0 \\ I_2 \end{bmatrix}$, $H_2 = \begin{bmatrix} 0 \\ -P_2(\chi) \end{bmatrix}$, and $P_2(\chi)$ is designed as bounded function.

To investigate the convergence of the estimation error of the designed sensor fault estimator, the Lyapunov function is given as follows:

$$V_f = \frac{1}{2}e_f^T A e_f, \tag{14}$$

where A is a designed positive definite matrix.

Invoking (13) and Assumption 1, the time derivative of V_f can be described as

$$\begin{aligned} \dot{V}_f &= e_f^T \dot{e}_f = e_f^T\Big(0.5\big(Q^T(\overline{x})A + A^T Q(\overline{x})\big)e_f + H_1\ddot{D} + H_2\Delta F(X_2)\Big) \\ &\le e_f^T\Big(0.5\big(Q^T(\overline{x})A + A^T Q(\overline{x})\big) + 0.5\|H_1\|^2 I_4 + 0.5\|H_2\|^2 I_4\Big)e_f + 0.5\tau_2^2 + 0.5\tau_3^2. \end{aligned} \tag{15}$$

From above process analysis, the following theorem can be obtained for the sensor fault estimator of suspension cable system of the unmanned helicopter.

Theorem 1. *Consider the suspension cable system of the unmanned helicopter (4) with sensor faults satisfying Assumption 1, the nonlinear sensor estimator is designed as (10). If the designed function parameters $L_1(X_1)$ and $L_2(\chi)$ are chosen to render the following inequality valid:*

$$Q^T(\overline{x})A + A^T Q(\overline{x}) + \|H_1\|^2 I_4 + \|H_2\|^2 I_4 < 0, \tag{16}$$

then the sensor fault estimation error is uniformly ultimately bounded.

In accordance with equations (15) and (16) and Lemma 1, we can make a conclusion that the sensor estimation error $\widetilde{D}$ is uniformly ultimately bounded.

4. Design of Robust Antiswing Control Plan Based on Sensor Fault Estimator

In this section, the fault-tolerant antiswing control law will be developed for the suspension cable system of the unmanned helicopter (4) with sensor faults based on the backstepping technique. The particular design steps are as follows.

Step 1: considering $e_1 = y - y_c$ and (9) yields

$$\dot{e}_1 = \dot{y} - \dot{y}_c = \dot{X}_1 - \dot{y}_c = \chi - D - \dot{y}_c. \tag{17}$$

To design the robust antiswing fault-tolerant control plan, we define

$$e_2 = \chi - \alpha_1, \tag{18}$$

where α_1 is a designed virtual control law.

Substituting (18) into (17) yields

$$\dot{e}_1 = e_2 + \alpha_1 - D - \dot{y}_c. \tag{19}$$

The virtual control law can be proposed as

$$\alpha_1 = -K_1 e_1 + \dot{y}_c + \widehat{D}, \tag{20}$$

where $K_1 = K_1^T > 0$ is a given parameter.

Substituting (20) into (19), we have

$$\dot{e}_1 = -K_1 e_1 + e_2 + \widetilde{D}. \tag{21}$$

Choose the Lyapunov function in the form of

$$V_1 = 0.5 e_1^T e_1. \tag{22}$$

Differentiating (22) and considering (21) yields

$$\begin{aligned} \dot{V}_1 &= e_1^T \dot{e}_1 = -e_1^T K_1 e_1 + e_1^T e_2 + e_1^T \widetilde{D} \\ &\leq - e_1^T (K_1 - 0.5I) e_1 + e_1^T e_2 + 0.5 \|\widetilde{D}\|^2. \end{aligned} \tag{23}$$

Step 2: differentiating (18), we obtain

$$\dot{e}_2 = \dot{\chi} - \dot{\alpha}_1. \tag{24}$$

Considering (9), (24) can be described as

$$\dot{e}_2 = F(X_1, \chi) + G(X_1) u + \dot{D}(t) + \Delta F(X_2) - \dot{\alpha}_1. \tag{25}$$

In this paper, the method of the dynamic surface control technique is introduced to acquire the derivatives of the virtual control law α_1 to handle the sensor fault D in the first step. Consider the following first-order filter $\overline{\alpha}_1$ as follows [2]:

$$\begin{aligned} \gamma \dot{\overline{\alpha}}_1 + \overline{\alpha}_1 &= \alpha_1, \\ \overline{\alpha}_1 (0) &= \alpha_1 (0), \end{aligned} \tag{26}$$

where $\gamma = \operatorname{diag}\{r_1, r_2\} > 0$ is a time constant.

By defining $e_l = \overline{\alpha}_1 - \alpha_1$, we have

$$\dot{e}_l = \dot{\overline{\alpha}}_1 - \dot{\alpha}_1 = -\gamma^{-1} e_l + \Delta_1 \left(\dot{y}_c, \widehat{D}, e_1 \right), \tag{27}$$

where $\Delta_1 (\dot{y}_c, \widehat{D}, e_1)$ is the sufficiently smooth vector in regard to $\Omega_1 (\dot{y}_c, \widehat{D}, e_1)$. It can be obtained that the smooth function $\Delta_1 (\cdot)$ is bounded on set $\Omega_1 (\cdot)$ with the maximum being Δ_{1m} [2].

In order to analyze the convergence of the first-order filter (24), the Lyapunov function candidate is given by

$$V_l = 0.5 e_l^T e_l. \tag{28}$$

Differentiating (29) and invoking (27), we obtain

$$\begin{aligned} \dot{V}_l &= e_l^T \dot{e}_l = e_l^T \left(-\gamma^{-1} e_l + \Delta_1 \left(\dot{y}_c, \widehat{D}, e_1 \right) \right) \\ &\leq - e_l^T \left(\gamma^{-1} - 0.5I \right) e_l + 0.5 \Delta_{1m}^2. \end{aligned} \tag{29}$$

To handle $\dot{D}(t)$, the sensor fault estimator (10) is used. Using the outputs of the sensor fault estimator and the first-order filter, the controller law is designed as

$$u = -G(X_1)^T \left(G(X_1) G(X_1)^T \right)^{-1} \left(K_2 e_2 + F(X_1, \chi) + e_1 + \dot{\widehat{D}}(t) - \dot{\overline{\alpha}}_1 - \beta \operatorname{Sign}(e_2) \right). \tag{30}$$

where $K_2 = K_2^T > 0$, $\beta > \tau_3$, are designed parameter and $\operatorname{Sign}(e_2) = [\operatorname{sign}(e_{21}), \operatorname{sign}(e_{22})]^T$.

Substituting (30) into (25), we obtain

$$\begin{aligned} \dot{e}_2 &= F(X_1, \chi) + \dot{D}(t) - \dot{\alpha}_1 + \Delta F(X_2) \\ &\quad - G(X_1) G(X_1)^T \left(G(X_1) G(X_1)^T \right) \left(K_2 e_2 + F(X_1, \chi) + \dot{\widehat{D}}(t) - \dot{\overline{\alpha}}_1 + e_1 - \beta \operatorname{sign}(e_2) \right) = -K_2 e_2 + \dot{\widetilde{D}} + \dot{e}_l - e_1 + \Delta F(X_2) - \beta \operatorname{Sign}(e_2). \end{aligned} \tag{31}$$

Considering (27), (31) can be written as

$$\dot{e}_2 = -K_2 e_2 + \dot{\widetilde{D}} - e_1 - \gamma^{-1} e_l + \Delta_1 \left(\dot{y}_c, \widehat{D}, e_1 \right) + \Delta F(X_2) - \beta \operatorname{sign}(e_2). \tag{32}$$

Choose the Lyapunov function candidate as

$$V_2 = 0.5 e_2^T e_2. \tag{33}$$

Differentiating (33) and considering (31) yields

$$\begin{aligned} \dot{V}_2 &= e_2^T \dot{e}_2 = -e_2^T K_2 e_2 - e_2^T e_1 + e_2^T \dot{\widetilde{D}} - e_2^T \left(-\gamma^{-1} e_l + \Delta_1 \left(\dot{y}_c, \widehat{D}, e_1 \right) \right) \\ &\quad + e_2^T \Delta F(X_2) - \beta e_2^T \operatorname{sign}(e_2). \end{aligned} \tag{34}$$

Considering $e_2^T \Delta F(X_2) - \beta e_2^T \operatorname{Sign}(e_2) < 0$, we have

$$\dot{V}_2 \leq - e_2^T \left(K_2 - I_2 - 0.5 \gamma^{-2} I_2 \right) e_2 - e_2^T e_1 + 0.5 \|\dot{\widetilde{D}}\|^2 + 0.5 e_l^2 + 0.5 \Delta_{1m}^2. \tag{35}$$

The following theorem is given to summarize the design of the robust antiswing control scheme studied for the suspension cable system of an unmanned helicopter with sensor fault.

Theorem 2. *For the studied suspension cable system of an unmanned helicopter with sensor fault, based on the nonlinear dynamic (4) satisfying Assumption 1 and Assumption 2, the nonlinear sensor fault estimator is designed as (10). By utilizing the designed sensor fault estimator, the robust antiswing control scheme is designed as (20), (26), and (30). Under the sensor fault estimator-based antiswing control of the suspension cable system of an unmanned helicopter, the closed-loop system is convergent and all signals are bounded.*

Proof. In order to prove the stability of the whole system, the Lyapunov function is selected as

$$V = V_f + V_1 + V_2 = \frac{1}{2}e_f^T e_f + 0.5e_1^T e_1 + 0.5e_2^T e_2. \tag{36}$$

Differentiating (36) and considering (15), (23), and (35), we have

$$\begin{aligned}\dot{V} \le{}& e_f^T\left(0.5\left(Q^T(\overline{x})A + A^T Q(\overline{x})\right) + 0.5\|H_1\|^2 I_4 + 0.5\|H_2\|^2 I_4\right)e_f + 0.5\tau_2^2 \\ &- e_1^T(K_1 - 0.5I_2)e_1 + e_1^T e_2 + 0.5\|\widetilde{D}\|^2 \\ &- e_2^T\left(K_2 - I_2 - 0.5\gamma^{-2}I_2\right)e_2 - e_2^T e_1 + 0.5\|\widetilde{\dot{D}}\|^2 + 0.5e_l^2 + 0.5\Delta_{1m}^2 \\ &- e_l^T\left(\gamma^{-1} - 0.5I_2\right)e_l + 0.5\Delta_{1m}^2 + 0.5\tau_2^2 + 0.5\tau_3^2.\end{aligned} \tag{37}$$

Using the definition $e_f = [\widetilde{D}^T, \widetilde{\dot{D}}^T]^T$, we have

$$\begin{aligned}\dot{V} \le{}& e_f^T\left(0.5\left(Q^T(\overline{x})A + A^T Q(\overline{x})\right) + 0.5\|H_1\|^2 I_4 + 0.5\|H_2\|^2 I_4 + I_4\right)e_f - e_1^T(K_1 - 0.5I_2)e_1 \\ &- e_2^T\left(K_2 - I_2 - 0.5\gamma^{-2}I_2\right)e_2 \\ &- e_l^T\left(\gamma^{-1} - I_2\right)e_l + \tau_2^2 + \Delta_{1m}^2 + 0.5\tau_3^2.\end{aligned} \tag{38}$$

Define

$$\begin{aligned}\kappa ={}& \lambda_{\min}\Big(\left(0.5\left(Q^T(\overline{x})A + A^T Q(\overline{x})\right) + 0.5\|H_1\|^2 I_4 + 0.5\|H_2\|^2 I_4 + I_4\right) - (K_1 - 0.5I_2), \\ &\left(K_2 - I_2 - 0.5\gamma^{-2}I_2\right), \left(\gamma^{-1} - I_2\right)\Big) \\ \rho ={}& \tau_2^2 + \Delta_{1m}^2 + 0.5\tau_3^2.\end{aligned} \tag{39}$$

Then, we have

$$\dot{V} \le -\kappa V + \rho. \tag{40}$$

From (40) and Lemma 1, we can conclude that $e_1 \longrightarrow 0$ when $t \longrightarrow \infty$. Thus, the tracking control goal is realized for the suspension cable system of an unmanned helicopter with sensor fault. This concludes the proof. □

5. Simulation Study

In the following, simulation results and analysis are given to illustrate the validity of the designed antiswing control of the suspension cable system of an unmanned helicopter based on the sensor fault estimator. The basic parameters of the suspension cable system of an unmanned helicopter are referred to [2] and are presented in Table 1.

In the given simulation analysis, the system initial conditions are given by $[X_1^T(0), X_2^T(0)] = [0, 0, 0, 0]^T$. The desired trajectories of an unmanned helicopter are as follows:

$$\begin{aligned} x_c &= 50\text{m}, \\ \theta_c &= 0^\circ. \end{aligned} \tag{41}$$

Furthermore, the sensor fault vector is given by

$$D = \begin{bmatrix} 0.15\sin(t) \\ 0.1\sin(t) \end{bmatrix}. \tag{42}$$

Table 1: System parameters.

Symbol	Unit	Value
M	kg	2000
m	kg	500
g	m/s^2	9.8
l	m	15

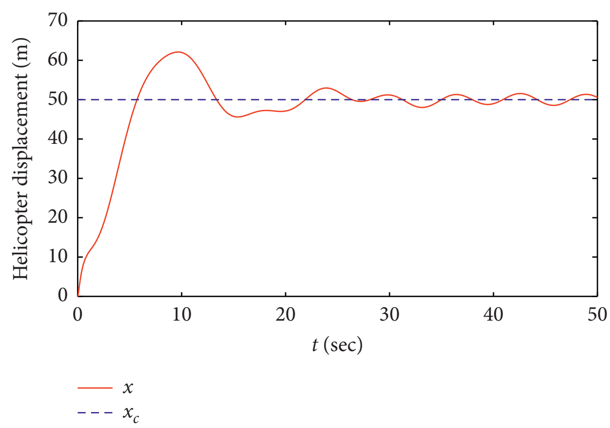

Figure 2: The tracking control result of the helicopter displacement x.

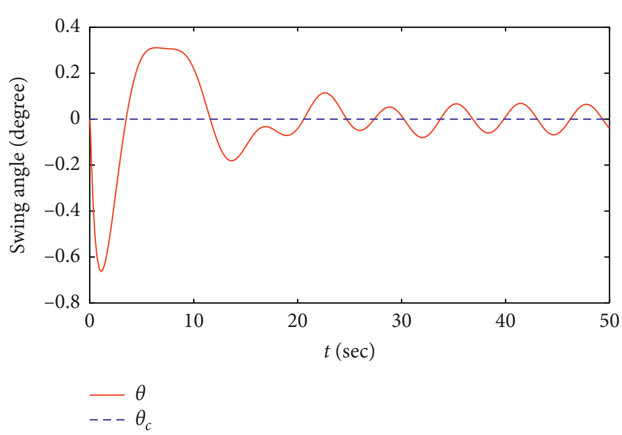

Figure 3: The tracking control result of the swing angle of hanging load θ.

The corresponding design parameters of the developed antiswing control of the suspension cable system of an unmanned helicopter based on the sensor fault estimator are chosen as $K_1 = I_2$, $K_2 = 150I_2$, and $\gamma = 0.5$. The nonlinear sensor fault estimator is designed as (10). Based on the designed sensor fault estimator, the robust antiswing control scheme is developed as (20), (26), and (30). The simulation results are presented in Figures 2–7.

Figures 2 and 3 show the tracking control result of the suspension cable system of an unmanned helicopter with sensor fault by using the designed robust antiswing control plan which can verify the effectiveness of the developed antiswing control method. The tracking control errors are presented in Figures 4 and 5. They can be seen that the tracing errors of the suspension cable system of an unmanned helicopter with sensor fault are convergent and bounded. Then, Figures 6 and 7 show the effectiveness of the developed sensor fault estimator. We can note that the estimation results $\widehat{D}$ are good and meet the antiswing performance requirement by using the developed sensor fault estimator. Specially, we can see that the swing angle of the load is small in the flight process. Thus, the antiswing performance is achieved under the sensor fault.

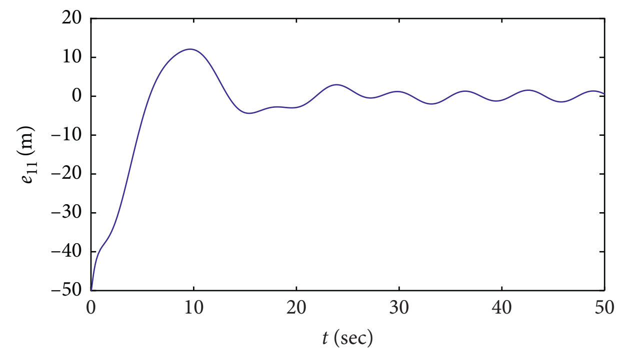

Figure 4: The tracking control error of the helicopter displacement x.

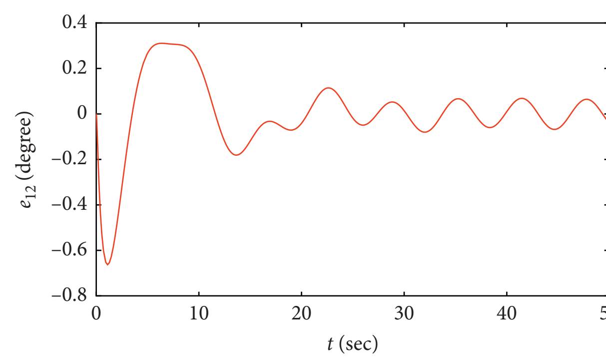

Figure 5: The tracking control error of the swing angle of hanging load θ.

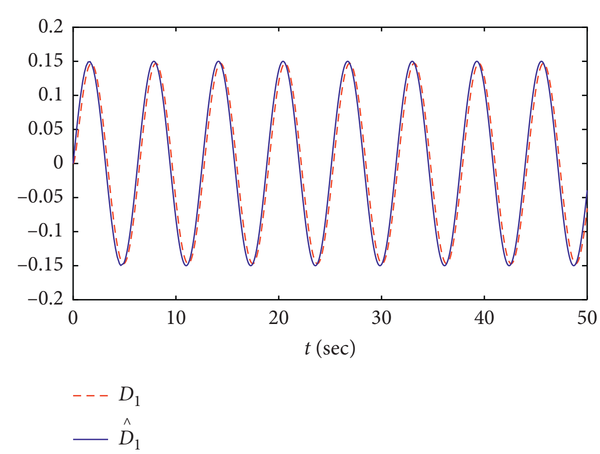

Figure 6: The estimation result of the sensor fault D_1.

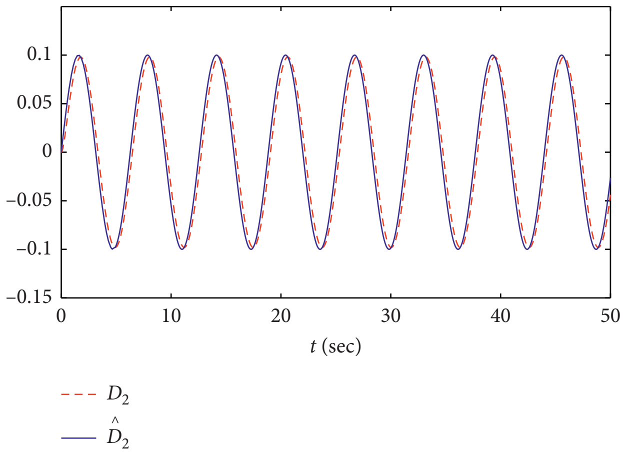

Figure 7: The estimation result of the sensor fault D_2.

On the basis of the given simulation results and analysis, we can draw a conclusion that the satisfactory antiswing control performance can be guaranteed for the suspension cable system of an unmanned helicopter based on the sensor fault estimator. Thus, the designed antiswing control scheme is valid for the suspension cable system of an unmanned helicopter.

6. Conclusion

The robust antiswing control scheme has been proposed for the suspension cable system of an unmanned helicopter with sensor fault. In order to tackle the sensor fault, a sensor fault estimator has been designed to estimate it. By using the output of sensor fault estimator, the robust tolerant control scheme has been developed to maintain the desired tracking control performance during the flight progress. In accordance with the designed antiswing controller, the system can track the desired trajectory and the whole system stability is guaranteed by using the Lyapunov method. Simulation results have been presented to show the efficiency of the studied antiswing control law for the suspension cable system of an unmanned helicopter with sensor fault. In the future work, the finite time sensor fault estimator can be designed for the suspension cable system of an unmanned helicopter.

Data Availability

The data used to support the findings of this study are available upon request to the corresponding author.

Conflicts of Interest

The author declares that there are no conflicts of interest.

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