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Robust Proportional Integral-State Feedback with Disturbance Observer for 2-DOF Helicopter System

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Abstract

This paper presents a new optimal robust control algorithm based on a proportional-integral (PI) and state feedback controller with a state disturbance observer for the two degrees-of-freedom helicopter system. A disturbance observer is used to improve the robustness of the proposed controller instead of using high gain to reject the external disturbance. Combining the PI controller with the state feedback controller improved the performance of the controlled system. Simulations based on Matlab 2022 are performed to compare the proposed controller with the linear quadratic regulator controller and investigate the performance and robustness of the proposed control method. The comparison between controllers was made under three cases: 1) nominal model, 2) disturbance rejection and 3) system uncertainty. The proposed algorithm shows good performance, which was confirmed clearly by the simulation results that illustrate the transient specifications represented by no overshot, the smallest settling time, and the smallest integral square error. The algorithm also indicates a good choice of objective function based on the infinity norm of the transfer function to ensure high robustness regardless of the external disturbance and parameter variations in the system.

Keywords: *Helicopter system; Robust control; PI controller.*

1. Introduction

Nowadays, helicopters are employed in different applications, including agriculture, civilian work and military. This expansion in helicopter applications has led researchers to develop different control methods to improve the performance of helicopter systems [1]. The challenge is that the helicopter system suffers from nonlinearity and high coupling between the pitch and yaw angles, in addition to its exposure to external disturbance and system uncertainties. A Quanser two-degrees of freedom (DoF) has been used to examine the control methods [2, 3]. LQR is widely used for creating the optimal controller for helicopter systems because of its efficiency and stability. In [4], adaptive control technology is provided with LQR, and the weighting matrices Q and R are selected for the best performance. The author combined LQR with model reference control, depending on the inverse Lyapunov function, enhancing the tracking performance by addressing external disturbances in the system [5]. A model reference adaptive control (MRAC) method is used with the LQR controller to improve the robustness of the helicopter system to address the issue of parameter variations [6]. Sliding mode controls (SMCs) have been successfully used to manage numerous linear and nonlinear systems [7]. In [8], the sliding mode with variable gain-based system states and tracking error without disturbance estimation was presented to control the orientation of the yaw angle. Jiang et al. suggest using the integral sliding mode control to regulate the helicopter system, improve the trajectory tracking and attenuate the effect of the disturbance by choosing the appropriate sliding surface [9]. Many methods have been suggested to improve SMC to control the helicopter system, including SMC with metaheuristics optimization algorithm [10], SMC with adaptive control [11], SMC with quantum logic [12], robust control with the same theory [13], super twisting SMC with particle filter [14], and SMC with fractional control and reinforcement learning [15]. However, chattering caused by a discontinuity in the control signal may be unsuccessful in the SMC because it can damage the actuator of the controlled system [9].

For the last few years, intelligent computing techniques, such as neural networks, fuzzy systems and genetic algorithms, have been successfully used to solve control challenges of various complicated systems. Neural networks and fuzzy logic have been effectively used to regulate various types of nonlinear systems [16, 17]. The fuzzy logic controller for the proposed controller's parameters is developed using metaheuristic methods and adaptive control theory for a 3-DOF helicopter system [18]. The genetic algorithm is enhanced to execute a fuzzy PID controller [19]. The best sliding mode controller variables to control a nonlinear helicopter model are adaptively determined using fuzzy logic [20].

The simplicity of a PID controller has motivated many researchers to use it in the control of different complex systems, and their performance improved by combining them with different control strategies [21]. In [22], MIMO PID controllers are presented to achieve the performance of a linear quadratic regulator for a 2-DOF helicopter system with bounded uncertainties. Raafat Shalaby et al. propose a fractional PID controller for a 2-DOF nonlinear helicopter system with the parameters of the proposed controller tuned by a machine learning algorithm and the stability analysis approved based Lyapunov theorem [23]. Although the previously proposed control methods have yielded good results, their implementation can pose some difficulties. Thus, this paper presents a state feedback tracking controller with a PI controller by using a disturbance observer that considers the simplicity of PI and the efficiency and stability of the state feedback controller. The two-DOF helicopter model and the linearization of the dynamic model are illustrated in the next section. Section 3 describes the procedures for designing the proposed robust PI-SFB controller. Section 4 presents the simulation results and discussion. The last part presents the conclusion.

2. Two-DOF Helicopter Model

Fig. 1 shows that the 2-DOF Helicopter model has two degrees of freedom represented by the pitch (ψ) and yaw (θ) angles. The yaw angle refers to motion around the Z axis, while the pitch angle refers to rotation around the Y axis. Helicopter systems have two blades, each driven by a DC motor. The motor input voltages are the control signals that determine the system's yaw and pitch angles to track the intended trajectory [24].

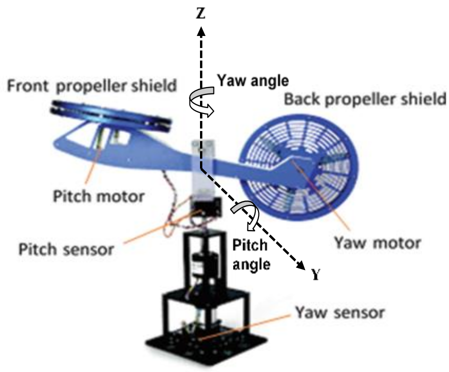

Fig. 1. Two-DOF helicopter system [25].

The nonlinearity of the helicopter dynamic model can be expressed as follows [10]:

$$\left(J_{pp} + ml^2\right)\ddot{\theta} = K_{pp}V_{pp} + K_{py}V_{yy} - B_{pp}\dot{\theta} + \zeta(t) \qquad \ldots(1)$$

$$\left(J_{yy} + ml^2 cos^2(\theta)\right)\ddot{\psi} = K_{yp}V_{pp} + K_{yy}V_{yy} - B_{yy}\dot{\psi} + \aleph(t) \qquad \ldots(2)$$

$$\zeta(t) = -ml^2 sin(\theta)\,cos(\theta)\,\dot{\psi}^2 - mglcos(\theta) \qquad \ldots(3)$$

$$\aleph(t) = 2ml^2\dot{\theta}sin(\theta)\,cos(\theta)\,\dot{\psi} \qquad \ldots(4)$$

where $\dot{\psi}(t)$ and $\dot{\theta}(t)$ represent the pitch and yaw velocities, respectively. K_{pp}, K_{py}, K_{yp} and K_{yy} are the thrust torque constants, and V_{pp} and V_{yy} are the input voltages to DC motors. J_{pp}, J_{yy}, B_{pp} and B_{yy} denote the moment of inertia and viscous damping about pitch and yaw axes, respectively. m

represents the mass of the system, l is the length and g is the gravitational acceleration. Table 1 lists the nominal values of these parameters.

Table 1. Parameters values.

Parameter	*Value*
K_{pp}	0.204Nm/V
K_{py}	0.006Nm/V
K_{yp}	0.021Nm/V
K_{yy}	0.072Nm/V
B_{pp}	0.800N/V
B_{yy}	0.318N/V
J_{pp}	0.038kg.m^2
J_{yy}	0.043kg.m^2
m	1.387kg
l	0.186 m

The linearized dynamic model of the helicopter system can be represented as follows:

$$\dot{x}(t) = Ax(t) + Bu(t) \quad \dots(5)$$
$$y(t) = Cx(t) \quad \dots(6)$$
$$x(t) = [\theta(t) \quad \psi(t) \quad \dot{\theta}(t) \quad \dot{\psi}(t)]^T \quad \dots(7)$$

where x is the state variables, u is the input and y is the output control.

$$u = [V_{pp} \quad V_{yy}]^T, y = [\psi(t) \quad \theta(t)]^T \quad \dots(8)$$

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & \frac{-(0.800\text{N/V})}{0.038\text{kg.m}^2+1.387\text{kg}(0.186\text{ m})^2} & 0 \\ 0 & 0 & 0 & \frac{-(0.318\text{N/V})}{0.043\text{kg.m}^2+1.387\text{kg}(0.186\text{ m})^2} \end{bmatrix} \quad \dots(9)$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{0.204\text{Nm/V}}{0.038\text{kg.m}^2+1.387\text{kg}(0.186\text{ m})^2} & \frac{0.006\text{Nm/V}}{0.038\text{kg.m}^2+1.387\text{kg}(0.186\text{ m})^2} \\ \frac{0.021\text{Nm/V}}{0.043\text{kg.m}^2+1.387\text{kg}(0.186\text{ m})^2} & \frac{0.072\text{Nm/V}}{0.043\text{kg.m}^2+1.387\text{kg}(0.186\text{ m})^2} \end{bmatrix} \quad \dots(10)$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \quad \dots(11)$$

3. Proposed Robust PI-SFB Controller Design

This section presents the design procedures of the proposed controller that integrates PI with state feedback (SFB) controllers. The parameters of the proposed controller are obtained by using an optimization algorithm to obtain maximum robustness against external disturbance and system uncertainty. Fig. 2 shows the block diagram of the proposed closed-loop system. Section 3.1 discusses the state feedback design, while section 3.2 presents a new control law that combines SFB with PI to achieve good tracking with high robustness against system uncertainty and external disturbance.

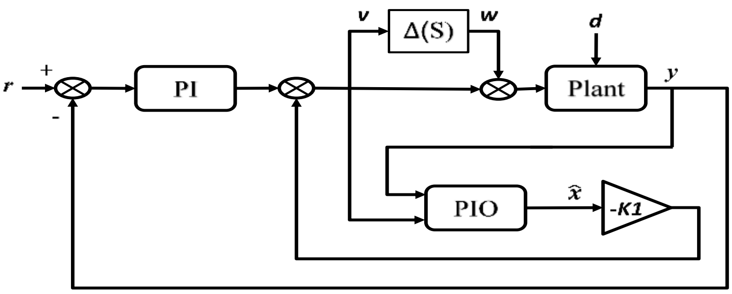

Fig. 2. Proposed robust control method.

3.1. State Feedback with PI

The proposed control law is composed of the state feedback term (u_{fb}) and PI term (u_i) as expressed below:

$$u = u_{PI} + u_{fb} \quad \dots(12)$$
$$u_{pi} = -k_p \int_0^{t_f} e(t)dt + k_i e(t) \quad \dots(13)$$
$$u_{fb} = -k_1\, x(t) \quad \dots(14)$$

The state space of the PI controller can be written as follows:

$$\dot{x}_{pi} = A_{PI}x_{PI} + B_{PI}(r - Cx) \quad ...(15)$$

$$u_{PI} = C_{PI}x_{PI} + D_{PI}(r - Cx) \quad ...(16)$$

where

$A_{PI} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$, $B_{PI} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$, $C_{PI} = [k_i \quad k_p]$, $D_{PI} = k_p$

In practice, measuring the states of the system is not easy; thus, an observer is used for estimating the states. In this paper, the proportional integral observer will estimate the state and disturbance.

3.2. Proportional Integral Disturbance – State Observer

The state space for the proportional integral observer (PIO) is expressed as follows:

$$\dot{d} = 0 \quad ...(17)$$

$$\dot{\hat{x}} = A\hat{x} + Bu_{fb} + L_P(y - C\hat{x}) + E\hat{d} \quad ...(18)$$

$$\dot{\hat{d}} = L_I(y - C\hat{x}) \quad ...(19)$$

where L_P and L_I denote the estimator gains for states and disturbance, respectively.

3.3. Augmented SFB–PI Control with PIO

The augmented state space for the proposed controller with the disturbance observer is expressed with a perturbation added to the system to discuss the robustness of the closed-loop feedback system.

Let

$$u = w + u_{PI} + u_{fb_2} - K_1\hat{x} \quad ...(20)$$

Then

$$\dot{x} = Ax + B(u_{PI} - K_1\hat{x}) + Bw + Ed \quad ...(21)$$

$$\dot{x} = Ax + B(C_{PI}x_{PI} + D_{PI}r - D_{PI}Cx) - BK_1\hat{x} + Bw + Ed \quad ...(22)$$

$$\dot{\hat{x}} = A\hat{x} - BK_1\hat{x} + B(C_{PI}x_{PI} + D_{PI}r - D_{PI}Cx) + L_PC(x - \hat{x}) + E\hat{d}$$

$$= (L_PC - BD_{PI}C)x + (A - BK_1 - L_PC)\hat{x} + BC_{PI}x_{PI} - BD_{PI}r + E\hat{d} \quad ...(23)$$

$$\dot{\hat{d}} = L_ICx - L_IC\hat{x} \quad ...(24)$$

Finally, the state space for the augmented system can be expressed as follows:

$$\begin{bmatrix} \dot{x} \\ \dot{x}_{PI} \\ \dot{\hat{x}} \\ \dot{\hat{d}} \end{bmatrix} = \begin{bmatrix} A - BD_{PI}C & BC_{PI} & -BK_1 & E \\ -B_{PI}C & A_{PI} & 0 & 0 \\ L_PC - BD_{PI}C & BC_{PI} & A - BK_1 - L_PC & 0 \\ L_IC & 0 & -L_IC & 0 \end{bmatrix} \begin{bmatrix} x \\ x_{PI} \\ \hat{x} \\ d \end{bmatrix} + \begin{bmatrix} B \\ 0 \\ 0 \\ 0 \end{bmatrix} w + \begin{bmatrix} BD_{PI} \\ B_{PI} \\ -BD_{PI} \\ 0 \end{bmatrix} r \quad ...(25)$$

The controller and observer gains will be tuned to obtain the minimum infinity norm of the system from $w(t)$ to $v(t)$ which is reciprocally called robustness bound. A closed loop system is always stable if it satisfies the following condition regardless of the value of perturbation:

$$\|\nabla(s)\|_\infty < \gamma \quad ...(26)$$

where

$$\|\nabla(s)\|_\infty \stackrel{\text{def}}{=} \sup \sigma(\nabla(jw)) \quad ...(27)$$

γ is the reciprocal of the infinity norm of the system from $w(t)$ to $v(t)$.

$$\gamma = \frac{1}{\|G(s)\|_\infty} \quad ...(28)$$

$G(s)$ represents the transfer function from $w(t)$ to $v(t)$.

Observer gain will be determined by setting the cost function of the optimization algorithm equal to the robustness bound.

4. Simulation Results

The Matlab 2022 program was used to simulate the helicopter system with two DOFs to investigate the effectiveness and performance of the proposed controller in terms of tracking and robustness. A comparison is made between the proposed controller and the standard LQR. The parameters of the proposed controller used in this simulation after using (fminsearch) function as an optimization algorithm are

$K_1 = \begin{bmatrix} 40.5 & 131.7 & 5 & 7.4 \\ -20.3 & 440 & -7 & 24 \end{bmatrix}$, $K_p = \begin{bmatrix} 46 \\ 100 \end{bmatrix}$, $K_i = \begin{bmatrix} 161 \\ 200 \end{bmatrix}$,

$L_P = \begin{bmatrix} 2.18 & 51.7 \\ 2.4 & 2.8 \\ 21.6 & 100 \\ -11.2 & 29.1 \end{bmatrix}$, $L_I = \begin{bmatrix} 17.3 & 100.7 \\ 200.1 & 90.1 \end{bmatrix}$.

While the parameters of standard LQR controller used are

$LQR = \begin{bmatrix} 30.1 & 1.1 & 6.6 & -0.2 \\ -0.05 & 3.1 & -1.5 & 5 \end{bmatrix}$.

4.1. Step Reference Tracking

This case discusses the performance of the proposed controller and the LQR controllers when the input is the unit step with a nominal model, and the simulation results are shown in Figures 3 and 4. The figures show that the proposed controller and LQR track the reference input successfully with approximately the same rise (t_r) and settling times(t_s) but no overshoot (M_p) can be observed in the proposed controller with high overshoot with the LQR controller. Tables 2 and 3 list the transient specifications for pitch and yaw models, respectively. The integral square errors (ISEs) for pitch and yaw models are shown in the tables. These performances clearly indicate that the proposed controller outperforms the LQR controllers.

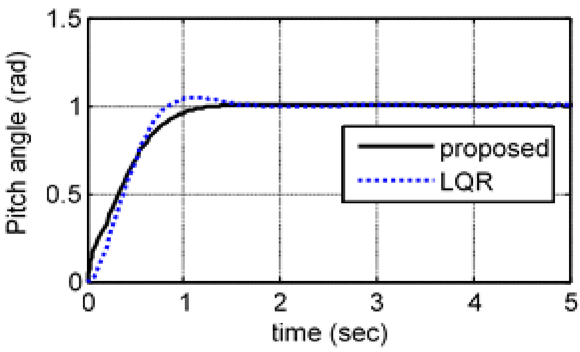

Fig. 3. Step response for pitch model.

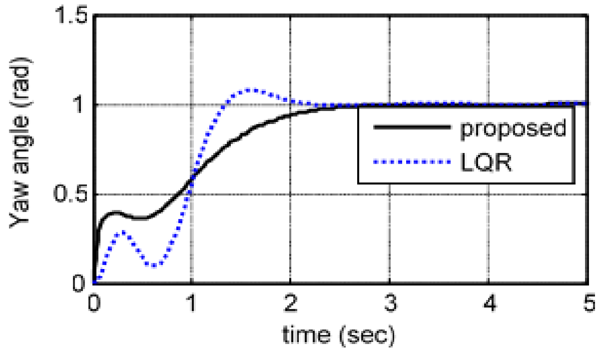

Fig. 4. Step response for yaw model.

Table 2,
Transient specifications for pitch model for nominal case.

Method	M_p	t_r**(sec)**	t_s**(sec)**	**IAE**
Proposed	0.6589	0.7683	1.1192	0.3821
LQR	4.7721	0.5479	1.4513	0.4165

Table 3,
Transient specifications for the yaw model for the nominal case.

Method	M_p	t_r**(sec)**	t_s**(sec)**	**IAE**
Proposed	0.0018	1.7572	2.4720	0.8251
LQR	7.5219	1.1112	2.0062	0.8981

4.2. Disturbance Rejection

A constant disturbance with amplitude 1 has been injected at t =3 sec to illustrate the robustness of the proposed control method. The simulation results shown in Figures 5 and 6 indicate the ability of the proposed controller to guide the trajectory of the system to the reference input, indicating robustness against external disturbance. These figures show the proposed controller quickly reached the reference signal and rejected the disturbance. The results indicate a high effect for disturbance in the case of LQR especially for the yaw model. Figures 7 and 8 show the integral square error for the pitch and yaw models, respectively. The proposed controller has the smallest IAE for both models, illustrating the superiority of the proposed controller. The results of this section indicate that the PI term, which is added to the state feedback controller, can reject the disturbance quickly, taking advantage of using a proportional integral observer that can estimate the state and disturbance correctly.

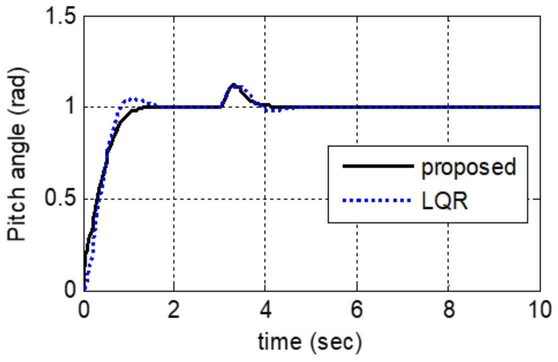

Fig. 5. Response pitch model for disturbance.

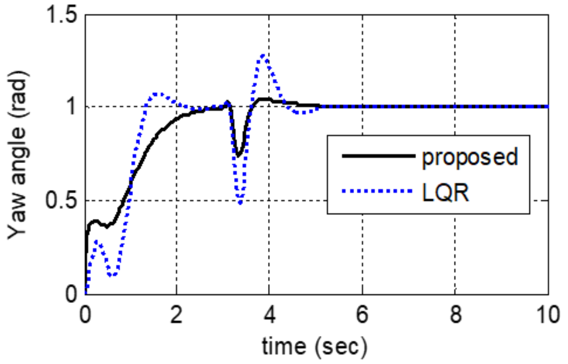

Fig. 6. Response yaw model for disturbance.

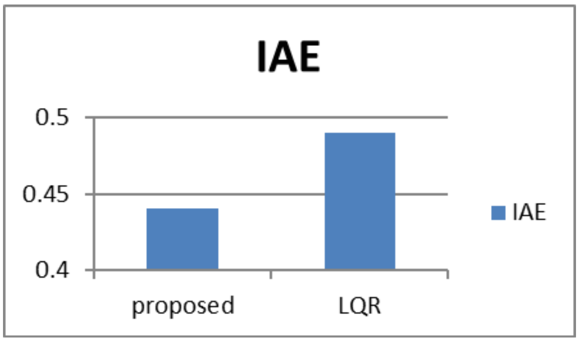

Fig. 7. IAE Variations of pitch model.

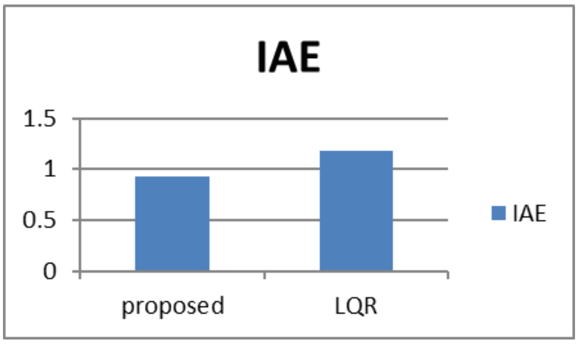

Fig. 8. IAE Variations of yaw model.

4.3. System Uncertainty

The parameters of the system have been changed to 20% of their nominal values to investigate the robustness of the proposed control method against the parameter variations. The simulation results, as shown in Figures 9 and 10, indicate the high robustness of the proposed controller against system uncertainties. The transient specifications, which are listed in Tables 4 and 5, illustrate the superiority of the proposed controller and show that the proposed controller's performance is not affected by system uncertainty. Moreover, the ISE show the high efficiency of the proposed controller in the presence of the parameter variations. The results of this section indicate a good choice of the objective function, which is based on the infinity norm of the transfer function to ensure good performance regardless of the variations in the parameters of the system.

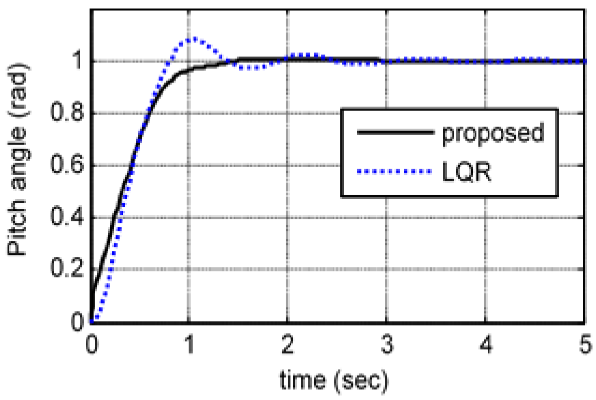

Fig. 9. Response pitch model for uncertainty.

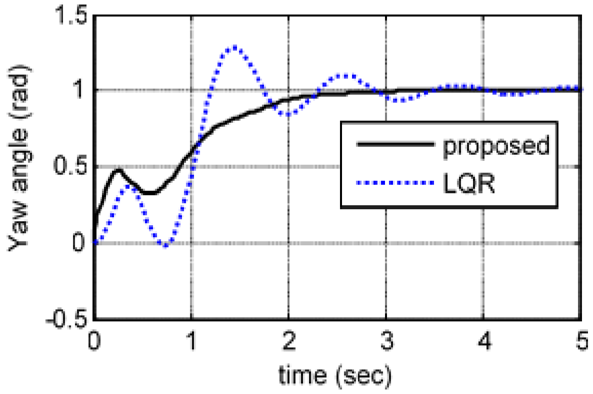

Fig. 10. Response yaw model for uncertainty.

Table 4,
Transient specifications for pitch model for uncertainty case.

Method	M_p	t_r(sec)	t_s(sec)	IAE
Proposed	0.7765	0.7224	1.1940	0.3812
LQR	8.1564	0.5406	2.2564	0.4538

Table 5,
Transient specifications for yaw model for uncertainty case.

Method	M_p	t_r(sec)	t_s(sec)	IAE
Proposed	0.0028	1.7858	2.5102	0.8252
LQR	28.5498	1.0329	4.3388	1.1384

5. Conclusion

This paper proposes a new robust and simple control method based PI and state feedback controllers with state and disturbance observers for a 2-DOF helicopter system. The system norm is used as a cost function to tune the parameters of the proposed controller and ensure the robustness of the proposed control method against external disturbance and system uncertainty. Three cases were used to examine the efficiency and robustness of the proposed controller. Simulation results show the high ability of the proposed method to reject the external disturbance and good performance in the presence of system uncertainty.

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متحكم التكامل النسبي المتين PI و رد الفعل الراجع مع مراقب الاضطراب لنظام طائرات هليكوبتر تتحرك بدرجتين من الحرية

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المستخلص

تقدم هذه الورقة خوارزمية تحكم جديدة مثالية ومتينة قائمة على متحكم التكامل النسبي (**PI**) ووحدة التحكم في رد الفعل الراجع (**SFB**) مع مراقب اضطراب الحالة لنظام طائرات هليكوبتر تتحرك بدرجتين من الحرية. تم استخدام مراقب الاضطراب لتحسين متانة وحدة التحكم المقترحة، بدلا من استخدام الكسب العالي لرفض الاضطراب الخارجي. في حين تم تحسين أداء النظام المتحكم به من خلال الجمع بين وحدة التحكم PI ووحدة التحكم في ردود الفعل الخاصة بالحالة. تم اجراء عمليات محاكاة تعتمد على Matlab 2022 لمقارنة وحدة التحكم المقترحة مع وحدة التحكم LQR, من أجل التحقق من أداء ومتانة طريقة التحكم المقترحة. تمت المقارنة بين المتحكمات في ثلاث حالات: 1) النموذج الاسمي 2) رفض الاضطراب 3) عدم يقين النظام. تظهر الخوارزمية المقترحة أداء جيد، والذي يمكن تأكيده بوضوح من خلال نتائج المحاكاة التي توضح المواصفات العابرة المتمثلة في عدم التجاوز، وأصغر زمن استقرار، وأصغر خطأ مربع متكامل. علاوة على ذلك، تشير هذه الخوارزمية إلى الاختيار الجيد لدالة الهدف بناءً على القاعدة اللامتناهية للدالة الرياضية لضمان متانة عالية بغض النظر عن الاضطرابات الخارجية وتغيرات المعلمات في النظام.