DIRECT SELF-REPAIRING CONTROL FOR HELICOPTER VIA QUANTUM CONTROL AND ADAPTIVE COMPENSATOR

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Abstract: A direct self-repairing control approach is proposed for helicopter via quantum control techniques and adaptive compensator when some complex faults occur. For a linear varying-parameter helicopter control system, the model reference adaptive control law is designed and an adaptive compensator is used for improving its self-repairing capability. To enhance anti-interference capability of helicopter, quantum control feedforward is added between fault and disturbance. Simulation results illustrate the effectiveness and feasibility of the approach.

Key words: helicopter; model reference adaptive control; self-repairing control; quantum control

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INTRODUCTION

Helicopters have many merits, such as not relying on the working conditions of the ground, the hovering, small flying-off and landing spaces[1], etc. However, a helicopter is a nonlinear, strong coupling, time-varying complex system with lots of uncertainties[2]. The adaptive controller is designed to control roll attitude[3] and the neural network is used to achieve attitude control on a tilt rotor helicopter rig[4]. A helicopter flight control law is designed using a learning control approach[5].

There are many actuator faults and external disturbance in the flight control systems of helicopter. The systems have many moving parts. Fault diagnosis and isolation[6] are more complex, so it is necessary to study the self-repairing capability of the flight control system. The self-repairing control law is usually designed based on the fault detection[7-8]. Meanwhile, it is a very difficult work to maintain the quick fault detection and the accurate control precision. Direct self-repairing control can achieve the self-repairing task without the fault diagnosis information[9-11], but has not been reported for a linear varying-parameter helicopter.

In recent years, quantum control technique[12-13] has increasingly been a hot research topic. The quantum evolutionary algorithm maintains a good balance between the coarse search and the strong search, so it has very good collaborative search capabilities and strong global search ability[14-16]. The results about the self-repair control using quantum control technology have not been reported yet.

A direct adaptive control approach is presented for the faulty helicopter control system using the fuzzy logic technique, but the external disturbance input is not considered[17]. In this paper, the model reference adaptive control law is designed and an adaptive compensator is used for improving its self-repairing capability. Furthermore, quantum control feedforward between fault and disturbance is added to increase the self-repairing control accuracy of helicopter in fault case. Simulation results illustrate the effectiveness and feasibility of the approach.

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1 MATHEMATICAL MODEL

The linear varying-parameter model[18] of helicopter is described by

$$\dot{\boldsymbol{x}}(t)=\boldsymbol{A}(\theta_t)\boldsymbol{x}(t)+\boldsymbol{B}(\theta_t)\boldsymbol{r}(t)+\boldsymbol{E}(\theta_t)\boldsymbol{f}(t)+\boldsymbol{N}\boldsymbol{n}(t) \quad (1)$$

$$\boldsymbol{y}(t)=\boldsymbol{C}\boldsymbol{x}(t) \quad (2)$$

where $\boldsymbol{r}(t)=[r_{col}, r_{lon}]$ is the control variable of helicopter, r_{col} and r_{lon} are the total distance variable and the longitudinal periodic variable, respectively; $\boldsymbol{x}(t)=[u, w, q, \theta]$ is the state variable, u and w are the horizontal and the vertical components, respectively, q is the pitch rate and θ the pitch angle; And

$$\boldsymbol{A}(\theta_t)=\begin{bmatrix}-0.036 & 0.027\ 1 & 0.018\ 8 & -0.455\ 5\\ 0.048\ 2 & -1.010 & 0.002\ 4 & -4.020\ 8\\ 0.100\ 2 & \theta_{t1} & -0.707\ 0 & \theta_{t2}\\ 0 & 0 & 1 & 0\end{bmatrix}$$

$$\boldsymbol{B}(\theta_t)=\begin{bmatrix}0.442\ 2 & 0.176\ 1\\ \theta_{t3} & -7.592\ 2\\ -5.522 & 4.490\\ 0 & 0\end{bmatrix},\ \boldsymbol{C}=\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}$$

where the parameter vector $\theta_t=[\theta_{t1}, \theta_{t2}, \theta_{t3}]$ is changing associated with the flight speed. When the speed is changed from 60 Kn to 135 Kn(1 Kn ≐0.514 m/s), $\theta_{t1}\in[0.066\ 4 \quad 0.504\ 7]$, $\theta_{t2}\in[0.119\ 8 \quad 2.523\ 0]$, $\theta_{t3}\in[0.977\ 5 \quad 5.112\ 0]$; $\boldsymbol{E}(\theta_t)$ is the transfer function matrix of injecting actuator fault of helicopter and $\boldsymbol{E}(\theta_t)=\boldsymbol{B}(\theta_t)$; $\boldsymbol{f}(t)$ is the actuator fault of helicopter, $\boldsymbol{N}\in\boldsymbol{R}^{4\times1}$ the order weighted matrix and $\boldsymbol{n}(t)$ the unknown interference.

The control system is unstable and the state feedback matrix $\boldsymbol{K}$ is used to make the control system stable[17], shown as

$$\boldsymbol{K}=\begin{bmatrix}15.895\ 7 & 0.495\ 7 & -4.943\ 7 & -11.391\ 8\\ 2.552\ 6 & -0.429\ 3 & -11.391\ 8 & -1.204\ 2\end{bmatrix}$$

2 DIRECT SELF-REPAIRING CONTROL

2.1 Model reference adaptive control

The flight quality of helicopter is worse when a fault occurs. When the model reference adaptive control law is designed, the flight control system has a strong self-repairing capability and good tracking performance, but it is still bad in horizontal speed and pitch angle. It cannot meet the requirement of the desired flight performance. In order to improve the flight control performance in faulty case, the model reference adaptive control approach for faulty helicopter is proposed using the outer loop adaptive compensation. The overall control structure is depicted in Fig. 1. The model reference adaptive controller is designed by Lyapunov's stability theory and the adaptive compensator is compensated separately by horizontal speed and pitch.

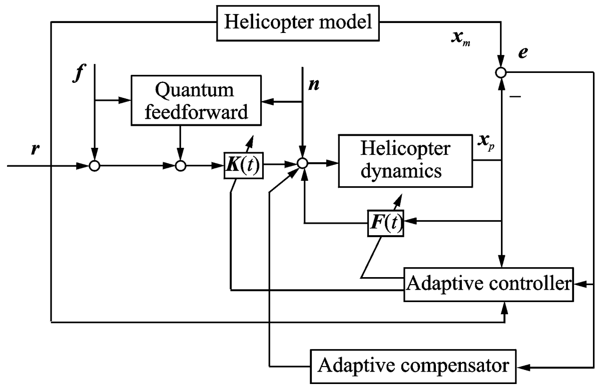

Fig. 1 Direct self-repairing control structure of helicopter

Suppose reference model is

$$\dot{\boldsymbol{x}}_m(t)=\boldsymbol{A}_m\boldsymbol{x}_m(t)+\boldsymbol{B}_m(t)\boldsymbol{r}(t) \quad (3)$$

$$\boldsymbol{y}(t)=\boldsymbol{C}_m\boldsymbol{x}_m(t) \quad (4)$$

where $\boldsymbol{A}_m\in\boldsymbol{R}^{n\times n}$, $\boldsymbol{B}_m\in\boldsymbol{R}^{m\times m}$, $\boldsymbol{C}_m\in\boldsymbol{R}^{n\times n}$.

The output response of the reference model is presentation of the desired output response of the helicopter control system when the given input is $\boldsymbol{r}(t)$. The generalized error is

$$\boldsymbol{e}(t)=\boldsymbol{x}_m(t)-\boldsymbol{x}_p(t) \quad (5)$$

In order to compensate changing parameters of helicopter, the feedforward gain matrix $\boldsymbol{K}(t)$ and the feedback gain matrix $\boldsymbol{F}(t)$, which are designed based on Lyapunov's stability theory, can be shown as

$$\boldsymbol{K}(t)=\int_0^t\boldsymbol{R}_1(\boldsymbol{B}_m\boldsymbol{K}^{*-1})\boldsymbol{P}\boldsymbol{e}\boldsymbol{x}_p^{\mathrm{T}}\mathrm{d}\tau+\boldsymbol{K}(0) \quad (6)$$

$$\boldsymbol{F}(t)=\int_0^t\boldsymbol{R}_2(\boldsymbol{B}_m\boldsymbol{K}^{*-1})\boldsymbol{P}\boldsymbol{e}\boldsymbol{r}^{\mathrm{T}}\mathrm{d}\tau+\boldsymbol{F}(0) \quad (7)$$

where $\boldsymbol{K}(t)\in\boldsymbol{R}^{m\times m}$, $\boldsymbol{F}(t)\in\boldsymbol{R}^{m\times n}$, $\boldsymbol{e}$ is the error signal, $\boldsymbol{K}^{*-1}$ the value of $\boldsymbol{K}(t)$ when the helicopter control model perfectly suit to the reference model, $\boldsymbol{P}$, $\boldsymbol{R}_1$ and $\boldsymbol{R}_2$ are the symmetry positive definite matrixes, $\boldsymbol{K}(0)$ and $\boldsymbol{F}(0)$ the initial values of $\boldsymbol{K}(t)$ and $\boldsymbol{F}(t)$.

The adaptive compensator is designed by equivalent compensator using error signal of horizontal speed and pitch angle. So horizontal speed equivalent compensator is μ_1, and pitch angle equivalent compensator is θ_1[19].
where

$$\mu_1 = \frac{K_1}{s+a}\mu_e \tag{8}$$

$$\theta_1 = \frac{K_2}{s}\theta_e \tag{9}$$

where K_1, K_2 and a are the undetermined coefficients. So the adaptive compensator $\boldsymbol{H}$ is

$$\boldsymbol{H} = \begin{bmatrix} \frac{K_1}{s+a} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{K_2}{s} \end{bmatrix} \tag{10}$$

2.2 Quantum control

In quantum computation, $|0\rangle$ and $|1\rangle$ denote the two basic states of micro-particles, which are named as quantum bit (qubit). Arbitrary qubit state can be expressed as the linear combination of two basic states. The state of qubit not only is $|0\rangle$ and $|1\rangle$, but also is a linear combination of the state, which is usually called as superposition state, namely

$$|\varphi\rangle = \alpha \cdot |0\rangle + \beta \cdot |1\rangle \tag{11}$$

where α and β are a pair of complex, called as the probability amplitude of quantum state. Namely, as the measurement result in quantum state, $|\varphi\rangle$ collapses $|0\rangle$ with a probability of $|\alpha|^2$ or collapses $|1\rangle$ with a probability of $|\beta|^2$. And they satisfy that

$$|\alpha|^2 + |\beta|^2 = 1 \tag{12}$$

Therefore, quantum state can be also denoted by its probability amplitude in the form of $|\varphi\rangle=[\alpha,\beta]^{\mathrm{T}}$. Obviously, when $\alpha=1,\beta=0$, $|\varphi\rangle$ is the basic state $|0\rangle$, which can be described by $|\varphi\rangle=[1,0]^{\mathrm{T}}$. Otherwise, when $\alpha=0,\beta=1$, $|\varphi\rangle$ is the basic state $|1\rangle$, which can be described by $|\varphi\rangle=[0,1]^{\mathrm{T}}$. Generally speaking, quantum state is the unit vector of two-dimensional complex vector space.

Due to the collapse of quantum states cased by observation, the quantum bit can be seen a continuous state between $|0\rangle$ and $|1\rangle$, until it has been observed. The existence of continuous state qubit and behavior has been confirmed by a large number of experiments. And there are many different physical systems can be used to realize quantum bit.

Similarly, three-qubit state can be expressed as

$$|\varphi\rangle = \alpha_{000}\cdot|000\rangle + \alpha_{001}\cdot|001\rangle + \alpha_{010}\cdot|010\rangle + \alpha_{011}\cdot|011\rangle + \alpha_{100}\cdot|100\rangle + \alpha_{101}\cdot|101\rangle + \alpha_{110}\cdot|110\rangle + \alpha_{111}\cdot|111\rangle \tag{13}$$

And the probability amplitude satisfies that

$$|\alpha_{000}|^2 + |\alpha_{001}|^2 + |\alpha_{010}|^2 + |\alpha_{011}|^2 + |\alpha_{100}|^2 + |\alpha_{101}|^2 + |\alpha_{110}|^2 + |\alpha_{111}|^2 = 1 \tag{14}$$

To increase the self-repairing control accuracy of helicopter in fault case, quantum control is added in the approach. The quantum feedforward module in Fig. 1 realizes the state description and control of three quantum bits, and the probability amplitudes of three quantum bits for the module can be seen in Table 1.

Table 1 Probability amplitudes of three quantum bits for quantum feedforward

Probability amplitude	Interference (Yes/No)			Fault (Yes/No)		
	Hanging wing 1	Hanging wing 2	Hanging wing 3	Hanging wing 1	Hanging wing 2	Hanging wing 3
α_{000}	No	No	No	No	No	No
α_{001}	No	No	Yes	No	No	Yes
α_{010}	No	Yes	No	No	Yes	No
α_{011}	No	Yes	Yes	No	Yes	Yes
α_{100}	Yes	No	No	Yes	No	No
α_{101}	Yes	No	Yes	Yes	No	Yes
α_{110}	Yes	Yes	No	Yes	Yes	No
α_{111}	Yes	Yes	Yes	Yes	Yes	Yes

3 STABILITY ANALYSIS

The helicopter control system can be transformed into a linear varying-parameter system, so the time-varying state equation can be analyzed. According to Fig. 1, the state equation of the faulty helicopter using the outer loop compensation technique can be described as

$$\dot{\boldsymbol{x}}_p(t) = \boldsymbol{A}_p(t)\boldsymbol{x}_p(t) + \boldsymbol{B}_p(t)\boldsymbol{r}_1(t) \tag{15}$$

where

$$\boldsymbol{r}_1(t) = \boldsymbol{K}(t)\boldsymbol{r} + \boldsymbol{F}(t)\boldsymbol{x}_p(t) + \boldsymbol{He}(t) \tag{16}$$

so

$$\dot{\boldsymbol{x}}_p(t) = [\boldsymbol{A}_p(t) + \boldsymbol{B}_p(t)\boldsymbol{F}(t)]\boldsymbol{x}_p(t) + \boldsymbol{B}_p(t)\boldsymbol{K}(t)\boldsymbol{r}(t) + \boldsymbol{B}_p(t)\boldsymbol{He}(t) \tag{17}$$

The generalized error state equation can be defined as

$$\dot{\boldsymbol{e}} = \boldsymbol{A}_m e + [\boldsymbol{A}_m - \boldsymbol{A}_p(t) - \boldsymbol{B}_p(t)\boldsymbol{F}(t)]\boldsymbol{x}_p(t) + [\boldsymbol{B}_m - \boldsymbol{B}_p(t)\boldsymbol{K}(t)]\boldsymbol{r} - \boldsymbol{B}_p(t)\boldsymbol{He}(t) \tag{18}$$

where $\boldsymbol{e}$ is the error signal, $\boldsymbol{A}_p(t)\in \boldsymbol{R}^{n\times n}, \boldsymbol{B}_p(t)\in \boldsymbol{R}^{n\times m}$. The fault can change the elements of the matrix. So the adaptive controller makes regular to $\boldsymbol{K}(t)$ and $\boldsymbol{F}(t)$. It makes the helicopter control system perfectly suit to the reference model, just as

$$\boldsymbol{A}_m = \boldsymbol{A}_p(t) + \boldsymbol{B}_p(t)\boldsymbol{F}^* \tag{19}$$

$$\boldsymbol{B}_m = \boldsymbol{B}_p(t)\boldsymbol{F}^* \tag{20}$$

where $\boldsymbol{K}^*$ and $\boldsymbol{F}^*$ are the values of $\boldsymbol{K}(t)$ and $\boldsymbol{F}(t)$ when the two models are suited perfectly. So Eq. (18) can be described as

$$\dot{\boldsymbol{e}} = \boldsymbol{A}_m\boldsymbol{e} + \boldsymbol{B}_m \boldsymbol{K}^{*-1}\widetilde{\boldsymbol{F}}\boldsymbol{x}_p + \boldsymbol{B}_m \boldsymbol{K}^{*-1}\widetilde{\boldsymbol{K}}\boldsymbol{r} - \boldsymbol{B}_p(t)\boldsymbol{He} \tag{21}$$

where $\widetilde{\boldsymbol{F}}=\boldsymbol{F}^* - \boldsymbol{F}(t)$ is the $m\times n$ order matrix, $\widetilde{\boldsymbol{K}}=\boldsymbol{K}^* - \boldsymbol{K}(t)$ the $m\times m$ order matrix.

Suppose the Lyapunov′ function is

$$\boldsymbol{V} = \frac{1}{2}[\boldsymbol{e}^{\mathrm{T}}\boldsymbol{Pe} + \mathrm{tr}(\widetilde{\boldsymbol{F}}^{\mathrm{T}}\boldsymbol{R}_1^{-1}\widetilde{\boldsymbol{F}} + \widetilde{\boldsymbol{K}}^{\mathrm{T}}\boldsymbol{R}_2^{-1}\widetilde{\boldsymbol{K}})] \tag{22}$$

where $\boldsymbol{P}, \boldsymbol{R}_1^{-1}$ and $\boldsymbol{R}_2^{-1}$ are the symmetrical positive definite matrixes, which guarantees $\boldsymbol{V}>0$.

$$\dot{\boldsymbol{V}} = \frac{1}{2}[\dot{\boldsymbol{e}}^{\mathrm{T}}\boldsymbol{Pe} + \boldsymbol{e}^{\mathrm{T}}\boldsymbol{Pe} + \mathrm{tr}(\dot{\widetilde{\boldsymbol{F}}}^{\mathrm{T}}\boldsymbol{R}_1^{-1}\widetilde{\boldsymbol{F}} + \widetilde{\boldsymbol{F}}^{\mathrm{T}}\boldsymbol{R}_1^{-1}\dot{\widetilde{\boldsymbol{F}}} + \dot{\widetilde{\boldsymbol{K}}}^{\mathrm{T}}\boldsymbol{R}_2^{-1}\widetilde{\boldsymbol{K}} + \widetilde{\boldsymbol{K}}^{\mathrm{T}}\boldsymbol{R}_2^{-1}\dot{\widetilde{\boldsymbol{K}}})] = \frac{1}{2}[\boldsymbol{e}^{\mathrm{T}}(\boldsymbol{PA}_m + \boldsymbol{A}_m{}^{\mathrm{T}}\boldsymbol{P})\boldsymbol{e}] + \boldsymbol{e}^{\mathrm{T}}\boldsymbol{PB}_m \boldsymbol{K}^{*-1}\widetilde{\boldsymbol{F}}\boldsymbol{x}_p + \boldsymbol{e}^{\mathrm{T}}\boldsymbol{PB}_m \boldsymbol{K}^{*-1}\widetilde{\boldsymbol{K}}\boldsymbol{r} - \boldsymbol{e}^{\mathrm{T}}\boldsymbol{PHe} + \frac{1}{2}\mathrm{tr}(\dot{\widetilde{\boldsymbol{F}}}^{\mathrm{T}}\boldsymbol{R}_1^{-1}\widetilde{\boldsymbol{F}} + \widetilde{\boldsymbol{F}}^{\mathrm{T}}\boldsymbol{R}_1^{-1}\dot{\widetilde{\boldsymbol{F}}} + \dot{\widetilde{\boldsymbol{K}}}^{\mathrm{T}}\boldsymbol{R}_2^{-1}\widetilde{\boldsymbol{K}} + \widetilde{\boldsymbol{K}}^{\mathrm{T}}\boldsymbol{R}_2^{-1}\dot{\widetilde{\boldsymbol{K}}}) \tag{23}$$

Eq. (23) can be described as

$$\dot{\boldsymbol{V}} = \frac{1}{2}[\boldsymbol{e}^{\mathrm{T}}(\boldsymbol{PA}_m + \boldsymbol{A}_m{}^{\mathrm{T}}\boldsymbol{P})\boldsymbol{e}] + \mathrm{tr}(\boldsymbol{x}_p\boldsymbol{e}^{\mathrm{T}}\boldsymbol{PB}_m \boldsymbol{K}^{*-1}\widetilde{\boldsymbol{F}} + \dot{\widetilde{\boldsymbol{F}}}^{\mathrm{T}}\boldsymbol{R}_1^{-1}\widetilde{\boldsymbol{F}}\Big) + \mathrm{tr}(\boldsymbol{re}^{\mathrm{T}}\boldsymbol{PB}_m \boldsymbol{K}^{*-1}\widetilde{\boldsymbol{K}} + \dot{\widetilde{\boldsymbol{K}}}^{\mathrm{T}}\boldsymbol{R}_2^{-1}\widetilde{\boldsymbol{K}}) - \boldsymbol{e}^{\mathrm{T}}\boldsymbol{PB}_p(t)\boldsymbol{He} \tag{24}$$

Because of Eqs. (6,7), Eq. (24) can be described as

$$\dot{\boldsymbol{V}} = \frac{1}{2}[\boldsymbol{e}^{\mathrm{T}}(\boldsymbol{PA}_m + \boldsymbol{A}_m^{\mathrm{T}}\boldsymbol{P})\boldsymbol{e}] - \boldsymbol{e}^{\mathrm{T}}\boldsymbol{PB}_p(t)\boldsymbol{He} \tag{25}$$

By Eq. (10), we can get

$$\boldsymbol{B}_p(t)\boldsymbol{H} = \begin{bmatrix} 0.442\,2 & 0.176\,1 \\ \theta_{t3} & -7.592\,2 \\ -5.522 & 4.490 \\ 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} K_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & K_2e^{-a} \end{bmatrix} = \begin{bmatrix} 0.442\,2K_1 & 0 & 0 & 0.176\,1K_2e^{-a} \\ K_1\,\theta_{t3} & 0 & 0 & -7.592\,2K_2e^{-a} \\ -5.522K_1 & 0 & 0 & 4.490K_2e^{-a} \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{26}$$

when $\boldsymbol{K}_1>0, \boldsymbol{B}_p(t)\boldsymbol{H}>0$, so $\dot{\boldsymbol{V}}<0$, which means that the control law can make the control system stable.

4 SIMULATION ANALYSIS

The values of $\boldsymbol{K}(t)$ and $\boldsymbol{F}(t)$ are relevant with $\boldsymbol{R}_1, \boldsymbol{R}_2$ and $\boldsymbol{P}$ according to the above derivation. Suppose $\boldsymbol{R}_1, \boldsymbol{R}_2$ and $\boldsymbol{P}$ are unit matrixes. In Eqs. (8,9), $\boldsymbol{K}(0)=0, \boldsymbol{F}(0)=0; K_1=4, K_2=50, a=20$. The simulation time is 40 s, the reference input is $\boldsymbol{r}=[5\ \ 5]$. The approach based on the model reference adaptive control of outer loop compensation helicopter is validated by injecting fault into helicopter in the paper. Suppose some complex faults are worse and worse with time, and can be described as

$$\boldsymbol{f}(t) = \begin{cases} 0 & 0\leqslant t<10 \\ 5 & 10\leqslant t<15 \\ 10 & 15\leqslant t<20 \\ 15 & 20\leqslant t<25 \\ 20 & 25\leqslant t<30 \end{cases} \tag{27}$$

Suppose some strong interferences are described as

$$\boldsymbol{n}(t) = \begin{cases} 0 & 0\leqslant t<10 \\ 5 & 10\leqslant t<15 \\ 10 & 15\leqslant t<20 \\ -15 & 20\leqslant t<25 \\ 20 & 25\leqslant t<30 \end{cases} \tag{28}$$

In this paper, the simulation results are shown in Fig. 2, where the curve 1 indicates the model reference output; The curve 2 indicates the output of the helicopter control system using the model reference adaptive control of helicopter with fault; The curve 3 indicates the output of the helicopter control system without interference, using direct adaptive control of helicopter with fault on the outer loop compensation; The curve 4 indicates the output of the helicopter control system with interference, using direct adaptive control of helicopter with fault on the outer loop compensation and quantum control feedforward.

From the simulation, the control quality of helicopter using the model reference adaptive control method is not so good. There are steady state errors. However, direct self-repairing control via quantum control and adaptive compensator makes the helicopter control system have stronger selfrepairing and anti-interference capabilities.

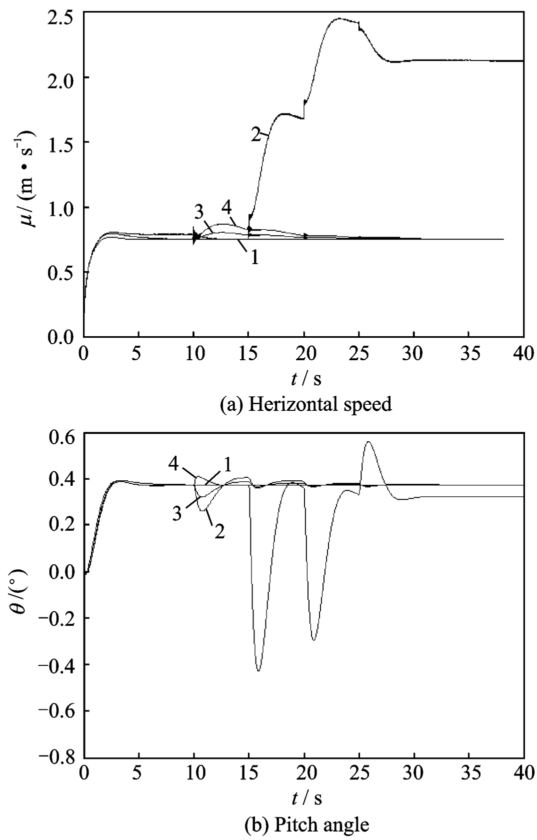

Fig. 2 Simulation results of helicopter control system

5 CONCLUSION

In this paper, a direct self-repairing control approach is proposed for the faulty helicopter control system by using outer-loop compensation and quantum control feedforward. The approach makes the outputs of the system track asymptotically the outputs of reference model without steady-state error. It is proved that the approach has stronger self-repairing and anti-interference capabilities.

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基于量子控制与自适应补偿器的直升机直接自修复控制

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摘要：针对发生复杂故障情况下的直升机采用量子控制理论与自适应补偿器技术进行直接自修复控制方法研究。首先对线性参数时变直升机控制系统进行模型参考自适应控制器设计；其次在外环增加自适应补偿器提高直升机控制系统的自修复控制能力，并利用李雅普诺夫稳定性理论证明了该系统的稳定性。最后为提高自修复控制律的抗干扰能力，在不影响系统稳定性的前提下，在故障信号与干扰信号之间增加量子前馈控制模块。仿真结果表明了该控制方法的有效性。

关键词：直升机；模型参考自适应控制；自修复控制；量子控制

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