A Robust Large Envelope Flight Controller Design Method based on the Particle Swarm Optimization Algorithm

Fan Zhanqi
College of Automation
Northwestern Polytechnical University
Xi'an, P.R.China
facrifanzhanqi@sina.com

Liu Lin
College of Automation
Northwestern Polytechnical University
Xi'an, P.R.China
fcd@facri.com

Sun Xun
College of Automation
Northwestern Polytechnical University
Xi'an, P.R.China
nwpusunxun@sina.com

***Abstract*—A robust flight control method based on the particle swarm optimization (PSO) algorithm is approved in this paper. Because of non-modeling dynamic character and parameter uncertainty are taken into consideration during the controller design process, the flight controller has strong robustness, excellent control performance and one robust controller could realize the large envelope flight control. In order to design the robust flight controller automatically and rapidly, the particle swarm optimization algorithm is used to select the weighting function. The simulation result shows that the weighting function could be designed automatically and rapidly, the flight controller has good performance and robustness.**

Keywords-robust; flight control; PSO; weighting function

I. INTRODUCTION

Robust control theory was developed in the 1980 of the 20th century, has gradually formed a relatively complete and mature theory system. Its design method is analysis of the uncertainty of the controlled object, and determines the uncertainty of controlled object. In the subsequent controller design, analytical method is used to design controller in order to meet system performance requirements, based on bias between the actual controlled object and uncertainty controlled object.

The H_{inf} theory in the robust control is proposed by the Zames[2]. The concept is to obtain robust stability controller. in the H_{inf} space through the infinite norm optimize. Domestic and foreign scholars do lots of research work in H_{inf} controller design. Dryden Flight Research Center design the H_{inf} flight control law for F/A-18 airplane. University of Cambridge design the H_{inf} flight control law for the thrust vector airplane[1-4].

Although the controller has good robust control performance, there is not determined and system design method for weighting functions. Currently the weighting functions are designed by qualitative rules, so the work is huge and complex. In this paper, non-modeling dynamic character and parameter uncertainty are taken into consideration during the controller design process. The robust Hinf mixed sensitivity control method is used to design flight controller. For the selection of the weighting function, POS algorithm is used to improve the design efficiency and flight control performance.

II. ROBUST H_{INF} MIXED SENSITIVITY CONTROLLER

In the H_{inf} robust controller design, non-modeling dynamic character and parameter uncertainty are taken into consideration during the controller design process. $\Delta G(s)$ represents non-modeling dynamic character, and $G_0(s,\Sigma)$ represents parameter uncertainty. The model of airplane could been expressed as:

$$G(s) = G_0(s,\Sigma)\left[I + \Delta G(s)\right] \tag{1}$$

The system matrix of equation is:

$$G_0(s,\Sigma):\begin{bmatrix} A_{G0}+\Delta A_{G0} & B_{G0}+\Delta B_{G0} \\ C_{G0} & D_{G0} \end{bmatrix} \tag{2}$$

Assuming that all of the elements of the aircraft state matrix A_f belong to a special interval:

$$A_f \in \left[U_1, U_2\right] \tag{3}$$

It could be proved that any $A_f \in \left[U_1, U_2\right]$ can be expressed as follows:

$$A_f = A_{f0} + E_f \Sigma_f F_f \tag{4}$$

Therefore parameter perturbations ΔA_{G0} and ΔB_{G0} can be expressed by the form of $\left[\Delta A_{G0} \quad \Delta B_{G0}\right] = E_{G0}\Sigma_{G0}\left[F_{a_{G0}} \quad F_{b_{G0}}\right]$.

Similarly,

$$E=\begin{bmatrix} E_{G0} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \Sigma=\begin{bmatrix} \Sigma_{G0} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

$$F_a=\begin{bmatrix} F_{a_{G0}} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} F_b=\begin{bmatrix} F_{b_{G0}} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

By introducing virtual disturbance signal w_p and evaluation signal z_p, the former can be converted to a standard H_∞ control issue and get augmented controlled object[5-6] as described by (5)-(7):

$$\dot{x} = Ax + \begin{bmatrix} E & B_1 \end{bmatrix} \begin{bmatrix} w_p \\ w \end{bmatrix} + B_2 u \quad (5)$$

$$Z = \begin{bmatrix} z_p \\ z \end{bmatrix} = \begin{bmatrix} F_a \\ C_1 \end{bmatrix} x + \begin{bmatrix} 0 & 0 \\ 0 & D_{11} \end{bmatrix} \begin{bmatrix} w_p \\ w \end{bmatrix} + \begin{bmatrix} F_b \\ D_{12} \end{bmatrix} u \quad (6)$$

$$y = C_2 x + D_{21} w + D_{22} u \quad (7)$$

By using a standard H_∞ control solution to (5)-(7), get flight controllers solution.

III. Weighting function selection based on the particle swarm optimization algorithm

Weighting function selection plays a very important role in meeting H_∞ mixed sensitivity which the flight control system required. Suitable weighting function can improve the robust stability, good tracking performance and anti-jamming capability. Currently, weighting function selection doesn't have a specified and systematic design method. It can be obtained by trail and error that makes design complicated and workload heavy. Thence, this paper uses weighting function selection based on the particle swarm optimization algorithm. This method avoids trail and error.

The principle of the particle swarm optimization algorithm is: PSO initialize a group of random particles, including particle position X_i and velocity V_i. After each an iteration, particle can update itself by tracking the two “"extremes” of particle optimal solution $Pbest$ and group optimal solution $Gbest$. After getting these two extremes above, the d-th Dimension particle can update its position and velocity by the following two equations:

$$V_{id} = \omega * V_{id} + c_1 * rand() * (Pbest - x_{id}) + c_2 * rand() * (Gbest - x_{id}) \quad (8)$$

$$X_{id} = X_{id} + V_{id} \quad (9)$$

V_{id} is the velocity of the i-th particle; X_{id} is the position of the i-th particle; $rand()$ is random number at the interval (0,1); c_1 and c_2 are study factor; ω is weighting coefficient.

Before selecting weighting function optimally, select fitness function as $F_r = C_{fr} - Q_r$, where Q_r is object function and is calculated by the formula $Q_r = k_1 \int_{t1}^{t2} t\left|e(t)\right|dt + k_2 T_r + k_3 \sigma$. The structures of W_S and W_T are diagonal matrixes:

$$W_S = diag(w_{S1}, \cdots, w_{Sm}) \qquad W_T = diag(w_{T1}, \cdots, w_{Tm}) \quad (10)$$

Weighting function optimal design process, based on the particle swarm optimization algorithm, is as follows:

- Step 1: The parameter to be optimized in the weighting function is coded as a particle. According to the design experience, determine the search space, and randomly generate the position and velocity of each particle in the particle group.
- Step 2: Determining each coefficient value in this optimal algorithm.
- Step 3: Each particle corresponds to a weighting function $W_S(t)$ and $W_T(t)$, design the control law for the aircraft model as shown by (5)-(7) by using standard H_∞ control solution, and then simulate it.
- Step 4: According to the results of the simulation, calculate the particle fitness value F_r.
- Step 5: Compare and update the particle optimal solution $Pbest$ and group optimal solution $Gbest$.
- Step 6: Update each particle's position and velocity according to equation (8)-(9).
- Step 7: Return to Step 3 until reaching the maximum number of iterations.

The above process can select weighting function automatically. It could make robust H_∞ aircraft controller design more simple and easy.

IV. Modeling and simulation

The 6-DOF nonlinear airplane model is built up as (11)-(24). Angle, the rate of angle and acceleration of angle use body coordinate.

$$\dot{V} = g(n_{xe}\cos\beta + n_z\sin\beta - (\cos\beta(\cos\alpha\sin\vartheta - \sin\alpha\cos\vartheta\cos\gamma) - \sin\beta\sin\gamma\cos\vartheta)) \quad (11)$$

$$\dot{\alpha} = \omega_z + (\sin\beta(\omega_y\sin\alpha - \omega_x\cos\alpha) + g/V(\cos\alpha\cos\vartheta\cos\gamma - n_{ye} + \sin\alpha\sin\vartheta))/\cos\beta \quad (12)$$

$$\dot{\beta} = g/V((n_z - \sin\gamma\cos\vartheta)\cos\beta + (\cos\alpha\sin\vartheta - n_{xe} - \sin\alpha\cos\vartheta\cos\gamma)\sin\beta) + \omega_y\cos\alpha + \omega_x\sin\alpha \quad (13)$$

$$\dot{\omega}_x = \frac{I_y}{I_x I_y - I_{xy}^2}(M_x - (I_z - I_y)\omega_y + I_{xy}\omega_x) + \frac{I_{xy}}{I_x I_y - I_{xy}^2}(M_y - (I_x - I_z)\omega_x - I_{xy}\omega_y) \quad (14)$$

$$\dot{\omega}_y = \frac{I_x}{I_x I_y - I_{xy}^2}(M_y - (I_x - I_z)\omega_x - I_{xy}\omega_y) + \frac{I_{xy}}{I_x I_y - I_{xy}^2}(M_x - (I_z - I_y)\omega_y + I_{xy}\omega_x) \quad (15)$$

$$\dot{\omega}_z = \frac{1}{I_z}M_z - \frac{I_{xy}}{I_z}(\omega_y^2 - \omega_x^2) - \frac{I_y - I_x}{I_z}\omega_x\omega_y \quad (16)$$

$$\dot{\vartheta} = \omega_y\sin\gamma + \omega_z\cos\gamma \quad (17)$$

$$\dot{\gamma} = \omega_x - \dot{\psi}\sin\vartheta \quad (18)$$

$$\dot{\psi} = (\omega_y\cos\gamma - \omega_z\sin\gamma)\big/\cos\vartheta \quad (19)$$

$$n_{ye} = n_y \cos\alpha + n_x \sin\alpha \qquad (20)$$

$$n_{xe} = n_x \cos\alpha - n_y \sin\alpha \qquad (21)$$

$$\begin{aligned} V_x = V(&\cos\beta(\cos\alpha\cos\vartheta\cos\psi - \sin\alpha(\sin\gamma\sin\psi \\ &- \cos\gamma\sin\vartheta\cos\psi) + \sin\beta(\cos\gamma\sin\psi \\ &+ \cos\psi\sin\gamma\sin\vartheta)) \end{aligned} \qquad (22)$$

$$\begin{aligned} V_y = V\,&\cos\beta(\cos\alpha\sin\vartheta - \sin\alpha\cos\vartheta\cos\gamma) \\ &- \sin\beta\sin\gamma\cos\vartheta) \end{aligned} \qquad (23)$$

$$\begin{aligned} V_z = \mathrm{V}(&\cos\beta(\cos\alpha(-\cos\vartheta\sin\psi)-\sin\alpha(\sin\gamma\cos\psi \\ &+\cos\gamma\sin\vartheta\sin\psi))+\sin\beta(\cos\beta\cos\psi \\ &-\sin\gamma\sin\psi\sin\vartheta)) \end{aligned} \qquad (24)$$

Linear model is obtained by the linearization method.

The number of the particle is select to 200. The study factor $c_1 = c_2 = 1.5$, weighting coefficient $w = 0.7$, the number of iterations is 200. The weighting function is designed by the PSO algorithm automatically and time consuming are 98 seconds，the results are:

$$W_S = \frac{25.7854(0.0031s+1)}{87.6593s+1}$$

$$W_T = \frac{0.0012(89.6358s+1)}{0.0031s+1}$$

Fig. 1 shows the curve of pitch angle. The fight height is 8000m, mach is 0.6 and pitch angle command is 15 degree. Fig. 2 shows the curve of pitch angle in the condition of +50% airplane model parameter perturbation. Fig. 3 shows the curve of pitch angle in the condition of -50% airplane model parameter perturbation. The flight controller designed by this method has good control performance.

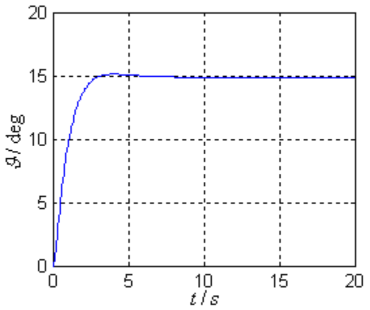

Figure 1. Pitch angle curve

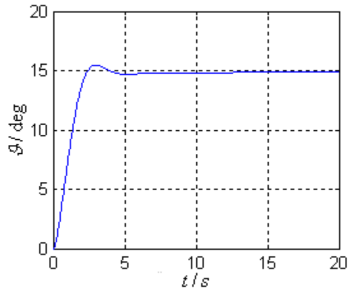

Figure 2. Pitch angle response

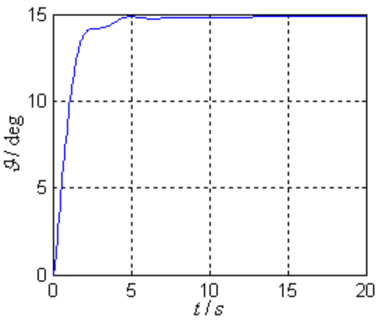

Figure 3. Pitch angle response

V. CONCLUSION

A robust flight controller design method based on the PSO algorithm is approved in this paper. Through non-modeling dynamic character and parameter uncertainty modeling, the large envelope mixed sensitivity design question is solved. Because of non-modeling dynamic character and parameter uncertainty are taken into consideration during the controller design process, only one robust controller could realize the large envelope flight control. The particle swarm optimization algorithm is used to select the weighting function, so the robust flight controller is designed automatically and rapidly. The simulation result shows that the flight controller has good performance and robustness.

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