Development of a Lateral-directional Envelop Protection Flight Control System

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Abstract—For the factor of aircraft flying safety, some critical flight parameters must be limited within the envelop borders. However, excellent flight performance requires that the aircraft can flight to some envelop borders easily and fast nearly. The purpose of envelop protection is to solve this dilemma. Based on the basic lateral-directional flight control law, an envelop protection method using control command compensation is developed. Numerical simulation results show that this method can effectively solves the flying safety problem without sacrificing flight performance.

Keywords- Aircraft, Envelop protection, Envelop limit, Command compensation, Flight control system, Lateral-directional control, Simulation

I. INTRODUCTION

Due to the factors of controllability, aircraft structure endurance and comfortability of passenger and crew, critical flight parameters of the aircraft should not exceed their borders, e.g. bank angle and sideslip angle. However, the best flight performances require flight to reach some envelop borders easily and fast nearly. Therefore, its flight control system must adopt envelop protection system to avoid risks when pilots try to reach envelop borders, and ensure pilot convenience manipulation.

II. TYPE STYLE AND FONTS

The lateral-directional envelop protection consists of bank angle protection and sideslip angle protection, which is an assistant function of the basic flight control law, as illustrated in Figure1.

In this system, Order shaping converts pilot forces into flight commands. Then the basic flight control law executes the track of these commands. The envelop protectors compensate the commands when flight parameters are about to exceeding their borders.

The principle of envelop protection design is as follows. For the rolling axis, the command is \( \dot{\phi} \), which is defined as the change rate of bank angle. The flight will hold the bank angle when \( \dot{\phi} \) recurs to 0. Therefore, bank angle protection requires \( \dot{\phi} \) to fast decrease to 0 when bank angle is near its border, as a result, bank angle stops increasing immediately.

For the yawing axis, both command and protect target is sideslip angle, therefore sideslip angle protection requires the command to keep being less than its border directly[1].

According to the principle of envelop protection, the envelop protector control law can be presented as follows.

\[
\begin{align*}
\dot{\phi} &= \begin{cases} 
   k_\phi \dot{\phi} + (k_\phi + k_\beta) \phi & \text{if } |\phi - \phi_{\text{lim}} - \Delta_\phi| \leq 0 \\
   k_\beta \dot{\beta} + (k_\beta + k_r) \beta & \text{if } |\beta + k_\beta \beta - \beta_{\text{lim}} - \Delta_\beta| \leq 0
\end{cases}
\end{align*}
\]

(1)

where \( \dot{\phi} \) and \( \dot{\beta} \) are the compensational commands, which amend respectively the pilot commands \( \dot{\phi}_b \) and \( \dot{\beta}_b \).

III. FLIGHT LATERAL-DIRECTIONAL CLOSED-LOOP CONTROL SYSTEM

As illustrated in Figure1, besides envelop protector, flight lateral-directional closed-loop control system mainly comprises flight lateral-directional dynamics model and basic flight lateral-directional flight control law.

A. Flight lateral-directional dynamics model[2]

For the aircraft dynamics, it is assumed that: the aircraft is in a straight and level flight. Small perturbation equation of flight lateral-directional linear dynamics model can be presented as follows.

\[
\dot{x} = Ax + Bu
\]

where

\[
A = \begin{bmatrix}
   Y_\beta & \alpha + \bar{Y}_\beta & \bar{Y}_r & -1 & g \cos \phi / V_r \\
   \bar{L}_\beta & \bar{L}_r & \bar{L}_r & 0 & 0 \\
   \bar{N}_\beta & \bar{N}_r & \bar{N}_r & 0 & 0 \\
   0 & 1 & \tan \theta & 0 & 0
\end{bmatrix}
\]

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where $\delta_a$ and $\delta_r$ denote disturbances about reference motion. $V_\alpha$, $\theta$, and $\phi$ denote respectively aileron and rudder input. $A$ and $B$ are presented in Formula (3).

$$
B = \begin{bmatrix}
0 & \bar{Y}_\phi \\
\bar{L}_\delta & \bar{\bar{L}}_\delta \\
\bar{N}_\delta & \bar{N}_\delta \\
0 & 0
\end{bmatrix}
$$

Amendment force and moment derivates in formula (3) are presented as follows.

$$
\begin{align*}
\bar{L}_i &= \frac{L_i + (I_{\omega} / I_i)N_i}{I_x - I_{\omega} / I_x} \\
\bar{N}_i &= \frac{N_i + (I_{\omega} / I_i)L_i}{I_y - I_{\omega} / I_y} \\
\bar{Y}_\beta &= \left(C_{\beta} - D_{\beta}\right) / mV \\
\bar{Y}_\alpha &= C_{\alpha} / mV
\end{align*}
$$

where $L_i$, $N_i$, and $C_i$ denote respectively rolling moment derivate, yawing moment derivate and side force derivate. $I_x$ and $I_y$ denote respectively moment of inertia in roll and yaw. $m$ denotes mass aircraft. $I_{\omega}$ denotes product of inertia about $ox$ and $oz$ axis.

B. Lateral-directional basic flight control law[3]

The structure of the basic lateral-directional flight control law is illustrated in Figure 2.

In the rolling axis, inner loop rate feedback improves damping of roll model. Bases on this, outer loop rate feedback and PI controller compose SCAS of rolling axis, which enables the flight responses track the command $\phi$. In the yawing axis, inner loop rate feedback improve yawing modal characteristic, outer loop yaw feedback and PI controller compose SCAS of yawing axis, which enables the flight responses track the command $\beta$.

Bases on the flight dynamics model and the basic flight control law, flight closed loop control system can be expressed with equation in matrix presented as follows.

$$
\begin{align*}
\dot{\phi} &= A\phi + B\delta \\
\dot{\beta} &= C\phi
\end{align*}
$$

IV. SIMULATION AND ANALYSIS

The simulation is implemented using flight lateral-directional closed-loop control system which includes envelop protectors. It starts at an initial condition of altitude $H=3000m$, velocity $V=160m/s$, in straight and level flight. Simulation curves are shown in Figure 3-4.

As Figure 3 indicates, before bank angle reaches its border $\phi_{lim}$, flight response of $\dot{\phi}$ follows the command $\dot{\phi}$, and bank angle keeps increasing. Without protection, bank angle $\phi$ excesses its border very soon, while $\dot{\phi}$ decreases to 0 and bank angle is limited under its border because of the compensational command $\dot{\phi}$ when bank angle protection is implemented. Simulation curves in Figure 4 also demonstrates sideslip angle protection can prevents sideslip angle from excessing its border $\beta_{lim}$.

Simulation result reflects the principle of envelop protection and satisfying effect.

V. SUMMARIES

Based on the lateral-directional basic flight control law, an lateral-directional envelop protection flight control system which adopt the method of control command compensation is designed. Simulation result demonstrates that the envelop protection system can effectively limits the protect targets under their borders.

REFERENCES


Figure 1. The lateral-directional flight control system

Figure 2. The Layout Lateral-Directional Basic Flight Control System
Figure 3. Bank angle protection simulation

Figure 4. Sideslip angle protection simulation