Research and Design of the Control Law of Passive Side-Stick System with Human Factor Fault

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Abstract. For modern commercial civil aircraft, failure tolerant control (FTC) method is the basic strategy. Human factor fault is becoming more and more important for the design of the active control technology for the electrical flight control system or fly-by-wire system (EFCS or FBW). This paper focuses on the problem caused by the human factor with passive side-stick equipment. A new design concept was proposed based on the Boeing and Airbus experience and a control law of feedforward structure with alarm functions was designed in MATLAB/simulink. The functions were tested in a flight simulation platform in a desktop simulator based on the open-loop dynamic model. The results showed that each part of the control law worked well and the functions were effective. The human factor failure problem of dual inputs was well solved. The work provided a reference for the designer in the civil aviation field especially for those of the developing modern commercial aircrafts.

1. Introduction
The fly-by-wire (FBW) control system equipped with the passive side-stick [1] has been generally applied to the modern large commercial civil aircraft. Compared with the conventional controls, the passive side-stick FBW enjoys the advantages of light weight, wide vision, large space, comfortable feel, etc. However, because of the lack of back-drive mechanism, the loss of human-machine or PF.pm information interaction is very likely to occur. And it may cause serious danger especially in case of emergency, e.g. In 2011, July the 22nd, in NO 34 runway of Narita International Airport of Tokyo, an accident occurred because the fuselage of the Airbus A-380 civil aircraft which carried 168 passengers slanted to right, and it led to a friction between the wing and the ground; It was not a unique instance, but had its counterpart. In 2009, October 28th, the tail of an Airbus A-320 civil aircraft which carried 147 passengers was destroyed because of the accident of friction. The two accidents above both occurred in the Airbus A series civil aircrafts which used the FBW equipped with passive side-stick as the control system. And it was concluded by analysis that the human error control caused by the inherent defect of the passive side-stick control system was the main reason of the air crash [2]. So the research of the passive side-stick control law is important for the civil aircraft safety. It is highly significant study work for Chinese civil aviation development.

This paper is organized as follows: in section 2, the design concepts of Boeing and Airbus experience about the control system of human-machine and PF.pm relationship is discussed. The control law structure is discussed in section 3. The section 4 shows the detailed design of our control law and simulation system. The simulation results are shown in section 5. And the section 6 is the conclusion.
2. Airbus and Boeing experience

In order to do our own design, a survey was made to get information of the recent passive side-stick system development and a scientific analysis of the design concept was made.

2.1. Man-machine authority distribution

According to the Airbus civil aircraft design concept [3,4], there exists a 'hard limit'. When the pilots do some unconventional handling, the Primary Flight Computer (FPC) will interfere with the pilots' inputs, so that the aircraft can remain in a preset orbit. Especially in case of emergency, the preset control law will rule. In contrast, the Boeing design concept is a 'soft limit'. The 'soft' means just suggesting but not interfering. In every case, the pilots of Boeing civil aircraft can hold the highest authority and the FPC provides the warning information by the cockpit (e.g. Flight Control Display and Primary Flight Display, PCD and PFD), the stick force gradient or something else. Sometimes, the plane can fly across the flight envelope.

The two concepts are both aimed at safety. The reason of the difference in concept is due to the difference of their cockpit control device, which is the difference between the passive side-stick of Airbus and the central stick with mechanical connections of Boeing. For the pilots, they certainly do not want their authority to be limited, but the lack of feedback information of the passive side-stick is very likely to let the pilots make mistakes, so that the protection measures and control laws such as pitch attitude protection, high angel-of-attack (AOA) protection and high speed protection are necessary. According to the Boeing design concept, there exists an override button, whose function is to get the highest control authority. For our design, to combine the advantages of the two design concepts was the basic idea. The key was the design balanced point between the override control and the effective protection. Furthermore it helped to deal with the man-machine authority distribution.

2.2. PF/PM authority distribution

PF and PM are the two pilots of the civil aircraft. It is easy to realize the information interaction by the mechanical linkages of the Boeing aircraft [5]. But for the passive side-stick system, the PF or PM sends the command to the flight control computer independently. It is very likely to occur that the PF and PM handled the side-stick at the same time which leads to an error dual input and that is the human factor fault. The designers of Airbus divide the dual handling inputs into three types, 'unintentional' 'intentional' and 'instinctive' [6,7]. Unintentional dual inputs always occur during the cruising flight, it is caused by the PM's touch without intention. The signal is always short in time and of small amplitude. The intentional dual inputs are always caused by the PM too. If the PM feels uncomfortable during the flight, he will handle the side-stick to adjust to suit the passengers. Owing to the handling of the PF, although the dual inputs last a long time, it will not lead to serious consequences. The instinctive dual inputs always occur in the take-off and the load phases. Especially in case of emergency, the PF and PM probably handle the side-stick fast with large amplitude. It is always the main reason of the friction accident.

In order to solve the problem of the passive side-stick to prevent the accident, the PF/PM authority must be well distributed. For our design of this part, the experience of Airbus is used and an advanced and reasonable design was made.

3. The structure of control law

There are two forms of the control law, feedback and feedforward. The feedback control laws are always based on the deviation adjustment. The feedback control laws always have time lag. In case of emergency, the lag is deathful. And the feedback control laws have closed control loop, so it relates to a problem of stabilization. In contrast, the feedforward control laws have the advantages of open loop stabilization, advanced control, less deviation, etc. In our designed simulation system, the control variable is measurable and the flight dynamics model is clear. It meets the requirement of the feedforward control design. So the feedforward structure was chosen in our design. And in the control close-loop, the control law is the feedforward part of the command channel.
4. Detailed design of the control law and the simulation system

In order to solve the problem well, the control law provided a lot of functions [8,9]. And the function helped deal with the man-machine and the PF\PM authority distribution to prevent the accident. The modularization designed control law had clear process and well defined functions [3]. In the design, the reasonable hardware and software were chosen to build a full simulation system. And the functions could be tested by the simulation system which is shown in figure 1. The process is consistent with the airbus golden rules [6,7].

4.1. The hardware input module

The function of this module was to collect the signal from the hardware and to send the digital signal to the after module [3]. Saitek X52 pro Joystick was chosen as the input hardware. The Saitek X52 pro Joystick is a kind of displacement joystick. People could handle the stick easily and the feeling was much closed to the passive side-stick [10,11]. The signal from the joystick was sent through the USB interface. The USB transmission speed is very quick and exact. And it sent the signal to the program development software—matlab\simulink. The joystick input module of Aerospace Blockset tools was used to complete the process. The signal consists of two parts, the three axis signal and the button signal. The function of passive side-stick hardware input was realized.

4.2. The feedforward control law

This module is the core of the whole control law. This part received the handling signal from the PF and PM as shown in figure 1. After the actuator model control, the module sent the processed data to the flight dynamic model and provided the warning signal to the warning module. In order to achieve the goal of finding the balance point between the Boeing and Airbus design concept, the control law we designed contained the functions below: 1) The short in time and small in amplitude signals will not be warned; 2) The authority of a single pilot will not be limited.; 3) The PF and PM can switch the authority through the priority logic module easily; 4) When the override button is pressed, the pilots will have the highest control authority. The structure is shown in figure 2. It is simple and clear and consistent with the FTC strategy trend of simplification.
4.2.1. The filter module. For the unintentional and intentional dual inputs, the Airbus set an initial stick force or a stick displacement-signal graph shown in Figure 3 in the passive side-stick system[1]. Although it could solve the two dual inputs situations, actually it limited the pilots' authority and the handling sensitivity and quality was not good.

The function of our filter module is to erase the small signals caused by the unintentional touch to prevent frequent alarm and send the result to the warning module. According to our design, the signals were not limited in this part, and criterion was provided to decide whether the warning module worked. After the filter, if the signal was zero, it meant it need not be warned. So the time and amplitude threshold in this part was important and according to the Airbus Flight system specification, if the value was less than 2degree and 500ms, the signal would not impact the flight much. And our initial filter threshold value was set 2degree and 500ms.

4.2.2. The threshold module. The design of the Airbus passive side-stick did not contain this module. So that the inputs sometimes could be so large that the transient response of the aircraft caused the accidents. And that is the reason why the module was set before the servo part. The threshold itself is a kind of limit, however, the dual inputs are wrong controls and the limits are reasonable. And in order to guarantee a single pilot's authority, the threshold value set initially was the max value of one-side stick. The value of Saitek X52 pro joystick is from -1 to 1 for the roll, yaw and pitch axis, 0 to 1 for the throttle. So in the design, the threshold values were set based on the hardware data. As the threshold module is also applied in the servo-loop, the servo-loop threshold value could be set double value of this module for the override function described in 4.2.5.

4.2.3. The passive side-stick priority logic module. According to the Airbus control, the take-over button could help the PF and PM switch the priority. When a pilot kept pressing the take-over button, the pilot had the input priority and the other pilot's input signal was shielded. After 40 seconds continuously pressing, the pilot would keep the priority. There were two disadvantages of the Airbus design. Long time keeping pressing made the pilots feel tired and in addition, once the priority was locked, it took time to switch the priority, and in case of emergency, the design was quite unfriendly.

In our design, the button actions are all short pressing. So the switching process is quick and convenient. Two buttons were set called 'take-over button' and 'lock button' on the joystick. The function of 'Take-over button' is to switch the handling priority in normal flight time. And the function of 'lock button' is to lock the priority to deal with the emergencies. The digital input of the button is 0, 1 for 'take-over button' and 0, 2 for 'lock button'. The priority level of 'lock button' is higher than the 'take-over button'. That means when the priority was locked, the 'take-over button' would lose its function. In order to achieve the button function of take-over and lock, the design of the whole logic was completed using some Simulink blocks. Besides, when this module worked, any dual inputs could be avoided. The output of the passive side-stick priority logic module was the Boolean number 0 and 1 which showed the priority of the PF and PM, 1 for yes and 0 for no. The module made the PF and PM switch the priority quickly, conveniently and comfortably, it helped deal with the PF\PM authority distribution.

4.2.4. The weighting coefficient module. This module worked when the 'instinctive' dual inputs occurred. If the PF and PM handled the passive side-stick at the same time and the signal was not zero after the filter, meanwhile the priority outputs of PF and PM were both 1, the module would set a weighting coefficient and multiply the signal by it. The weighting coefficient could help reduce the impact of the dual inputs and it made the pilots' responsibility and authority clear in case of dual inputs. In our design, the initial number was. That meant when the dual inputs happened only the inputs of PF was effective and the PF would take the full responsibility. The coefficient value would be set by the PF and PM before the flight. In order to avoid large inputs, it is suggested that, so that the responsibility and authority were clear and the PF/PM authority distribution was well dealt with.
4.2.5. The override button module. The design concept of override button came from the Boeing aircraft. The function of the override button was to provide the highest control authority to the pilots. In our design, when the override button was pressing, the two pilots' inputs will be sent to the dynamic model directly without any limit and dual inputs were allowed. The input amplitude value was 2 times of the original, and the pilots could give full play to the flight performance.

In our design, the function of the override button was merely to disconnect the feedforward control law, so we provided enough data interface for the further study to improve the function of this module.

4.3. 6 DOF dynamic model. We chose the B-747 parameters to build the 6 DOF dynamic model. B-747 is a classical commercial civil aircraft. The aerodynamic and geometry parameters have been published. In the design, we made some assumptions to simplify the equations: the influence of the earth rotation was ignored; the plane was seen as a rigid body; the change of the plane was ignored during the process.

According to the survey of the passive side-stick, the side-sticks were always handled in the take-off phase and the landing phase. So we chose the aerodynamic data in such phase. And then we simplified the 12 dynamic equations and got the small perturbation linear equation set. The form of the equation set is as follows:

\[ X = AX + BU \]  

According to the initial conditions, the linear equation set was divided into 2 equation sets, which we called longitudinal dynamic model and lateral dynamic model. The form of the two models is as follows:

\[ \dot{X}_\theta = A_\theta X_\theta + B_\theta \delta_e \]  

\[ \dot{X}_{\psi\phi} = A_{\psi\phi} X_{\psi\phi} + B_{\psi\phi} \begin{bmatrix} \delta_a \\ \delta_r \end{bmatrix} \]  

[\delta_e, \delta_a, \delta_r] is the deflection of the elevator, aileron and the rudder. We call it controlled variable. \( X_\theta = [V, \alpha, q, \theta, z, x]^T \), \( X_{\psi\phi} = [\beta, p, r, \phi, \psi, y]^T \) they are the 12 quantities of state. \([x, y, z]\) stands for the displacement; \([\psi, \theta, \phi]\) stands for the 3 attitude angle; \([p, q, r]\) stands for the 3 attitude rate; \([\alpha, \beta, V]\) is the angle of attack, angle of side slip and air speed. The matrix A and B are the state space matrix and input matrix. The numerical value of A and B were from the B-747 sea level aerodynamic data.

The dynamic model module received the signal of the deflection of the control surface from the joystick signal. Then the 12 linear equations were solved and we got the 12 quantities of state. The process is shown in figure 1. The output of this module was the flight quantities of state, and they were sent to the visual flight module and the warning module.

4.4. Warning module
The function of warning module is to provide the alarm information. There were 3 situations we thought should be warned.

4.4.1. Dual inputs warning. The criterion of the dual inputs came from the priority logic module and filter module. If none of the four output values were zero, we provided the warning signal. In this part, a logical AND module was set to achieve the goal.

4.4.2. Tail warning. The criterion whether the warning signal was provided was based on the result of calculation. In the body coordinate frame, we assume the tail coordinate is \( \xi_t = [-\delta_t, 0, 0] \). The transition matrix from the body coordinate frame to the earth-surface inertial reference frame is \( \mathcal{L} \).
\[
L = \begin{bmatrix}
\cos \theta \cos \psi & \sin \theta \sin \phi \cos \psi - \cos \phi \sin \psi & \sin \theta \cos \phi \cos \psi + \sin \phi \sin \psi \\
\cos \theta \sin \psi & \sin \theta \sin \phi \sin \psi + \cos \phi \cos \psi & \sin \theta \cos \phi \sin \psi - \sin \phi \cos \psi \\
-sin \theta & \sin \phi \cos \theta & \cos \phi \cos \theta
\end{bmatrix}
\]  

(4)

So in the earth-surface inertial reference frame we have:

\[
(\mathbf{\xi}_r)_g = \begin{bmatrix} x \\ y \\ z \end{bmatrix} + L (\mathbf{\xi}_r)_b
\]

(5)

We get:

\[
\begin{bmatrix} 0 \\ 0 \\ z_g \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} - L \begin{bmatrix} -\xi_x \\ 0 \\ 0 \end{bmatrix}
\]

(6)

And in the two frames we have \( h = -z \) and \( h_g = -z_g \) where \( h \) is the height.

After simplifying, we get:

\[ h = h_{\xi_x} + \sin \theta \xi_x \]

(7)

Equation (7) shows the relationship between the center of mass height and the tail height. If \( h_{\xi_x} < 0 \), then the accident would take place. We fitted a curve with cubic function based on the equation (7) to find the safety limits as shown in figure 4.

\[
\theta = 0.001h^3 - 0.0367h^2 + 1.8902h - 0.7063
\]

(8)

4.4.3. Wingtip warning

The wingtip warning criterion had the similar solution procedure with the tail warning. In this paper, the height result is as follows:

\[ h = h_{\xi_r} + \sin \theta \xi_x \]

(9)

Where the wingtip coordinate is \( \xi . \ell = ( -\xi_x, -\xi_y, 0 ) \) and \( \xi . r = ( -\xi_x, \xi_y, 0 ) . \)

Finally, the warning signals were sent to an interface to the computer sound card and the visual software. So the pilots could get the visual and auditory warning information and the safety of the flight would improve.

4.5. Visual flight module

The visual flight module was designed to turn the simulation result into animation [12,13]. And it provided the direct visual feelings. The free open source software FlightGear was chosen to provide the visual window. The FlightGear had the global terrain database and a variety of aircraft picture. Its internal data interface made it easy to connect to the matlab/Simulink.

The visual flight module consists of four Simulink modules. The four modules were all from the aerospace block set tool. When the simulation experiment was made, the simulation system first got the input signal from PF and PM through the passive side-stick interface module. Then the feedforward control law module process the signal and provided the deflection of each control surface and the priority signal of the PF and PM. The 6 DOF dynamic model sent the flight quantities of state to the visual software. The warning module sent the alarm information to the computer sound card. At last, the PF and PM could receive the visual information from the computer window and sound information from the sound card. And they make the next decision. The flight data were saved to the workspace and the data curve could be seen at any time. Figure 5 shows the pilots' first-person spatial perspective.
5. Simulation Results

In order to test and verify the functions of each module accurately, the inputs of each module were from the Simulink source modules instead of the passive side-stick hardware. However, some results were appeared as the sound and animation, e.g. the warning module and the visual flight simulation module and the function of the override button module is to disconnect the control law. The simulation results of them are difficult to show in this paper. Actually, those modules had been all tested in the desktop simulator and the functions were all effective.

5.1. Filter module

The signal with perturbations was sent to the filter module in the test and the result is shown in figure 6. The curve shows that the filter module can filter the small-amplitude and short-time signals and prevent the frequent alarm. The result was the same as expected.

5.2. Weighting coefficient module

The test signals of this part are sinusoidal signals of different initial conditions. Figure 7 and figure 8 show the two results of the weighting parameter module. Figure 7 shows that the PF and PM handle the passive side-stick at the same time in the same direction. Figure 8 shows the situation that the PM's operation is wrong and just opposite the PM. The results show that the module has good correction capability. And without side-stick logic, the PM would always have the priority and be responsible for the flight process. It was quite recommended that the weighting coefficient of the pilot who has more experience is set 1. So the human factor error could be reduced greatly.

5.3. Threshold module

Figure 9 shows the result of the threshold module. Although, the output of the threshold module does not quite tally with the expected, it increased the input amplitude. The expected function of the module was to keep the input amplitude from being too large, so the module achieved the goal.

5.4. Priority logic module

Figure 10 is the button inputs of the PF and PM. Figure 11 is the priority outputs of them. In order to test the 'take over' and 'lock' function of the module, a special input signal is set as shown in figure 10. During the first two seconds, the inputs of the button were both zero, so the priority of the PF and PM were both 1. From the 2nd second to the fifth second, the inputs were only 1 and 0, and the figure 11 shows the 'take-over' priority switch function. From the fifth second to the tenth second, the inputs were 2 and 0, and the figure 11 shows the 'lock' priority switch function. We observed that during the ninth second, the input signal of PM is 1, but it didn't work. So the function of 'take-over' and 'lock' was effective. Actually, there are 63 possible situations in this logic module, when figure 10 and 11 are typical results. It had been confirmed that every tested result could meet the function requirement.

5.5. The result of the angle of pitch

If a command signal is send to the dynamic model to change the parameter, the longitudinal states will change. Figure 12 and figure 13 show the results of the angle of pitch with and without control by
some dual inputs. The value reduces from 58.7 degree to 25.4 degree in weighting coefficient control and from 58.7 degree to 26.1 degree due to the threshold. The results indicated that the feedforward control law was effective. The two modules both reduced the open loop responses and the flight safety and flight quality were improved. Actually, if no dual inputs happened, there was no difference between the two result curves and it met the requirement in section 4.2. Consequently, the control law solved the problem of dual inputs.

![Simulation result](image1)

**Figure 6** Filter Simulation Result

![Simulation result](image2)

**Figure 7** the Same Direction

![Simulation result](image3)

**Figure 8** Opposite Direction

![Simulation result](image4)

**Figure 9** Threshold Result

![Priority button input](image5)

**Figure 10** Priority of PF and PM

![Priority button input](image6)

**Figure 11** Logic button inputs of PF and PM

![PM=1 and PF=0](image7)

**Figure 12** PM=1 and PF=0

![Threshold value=1](image8)

**Figure 13** Threshold value=1
6. Conclusion
This paper studied the passive side-stick control system in the civil aircraft and found the disadvantage and design defect with human factor of it. In order to solve the problem, a new design concept was put forward for the passive side-stick control system from the Airbus and Boeing's design. We improved the design of the Airbus and combined the advantage of the Boeing design and the possible human factors were considered in the function design of the control law with feedforward structure. The visual flight simulation system could help test and verify the functions of the control law and also it was a good platform for the aerospace researchers. The simulation results showed that the functions of each module were effective, and the design could help reduce the human factor error operations. So it would surely reduce the number of the air crashes. The flight safety and quality were both improved especially in the Load\Take-Off phase.

The research and design have great significance for the aircraft safety. Above all, the design is beneficial to the development of our country's aviation industry especially the design development of the commercial large civil aircraft.

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