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ATTITUDE PROTECTION FOR SIDE STICK-OPERATED AIRCRAFT – THE CLASSIC APPROACH

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Keywords: *attitude protection; attitude envelope; ground proximity; side stick*

Abstract

The side-stick operation characteristic would cause overlapping of the stick commands, which could lead to an impact accident during taking off or landing stages. The attitude envelope is designed to avoid the dangerous situations. Besides, the control law based on the two-stage polyline restriction scheme is developed to organize the attitude protection control system. Based on the simulation flight test results, the aircraft performs a safe flight well within the attitude envelope with protection. The proposed attitude protection system is believed to be applicable.

1 Introduction

Side stick-operation has been broadly used in modern aviation aircrafts whereas there are some innate drawbacks of the aircraft operated by side sticks. Typically, they do not provide direct feedback of the stick force, and the stick on each side works independently without mechanical interconnection. This might be challenging for the pilots to perceive real-time aircraft state and manual control status of the other pilot. Control signals from two pilots could be added, and an overlapping of stick command will happen. In adverse cases, an abrupt change of the aircraft state will be encountered. The composed signal could lead to a sharp variation of flight attitude, which is dangerous and is not supposed to happen.

Studies in side-stick controllers have discussed the methods to improve the operation quality. In a passive side-stick flight control interface, the control authority given to the pilot can be restricted to prevent over stressing the aircraft structurally and to keep the aircraft in the flight envelope [1], but the command signals from opposite stick are not delivered to the other. The cross-cockpit coupling technology provides the stick force and displacement to the opposite stick, but this characteristic addresses the pilot/copilot ambiguity problem, which allows the pilots to engage in a “force fight” [2, 3].

In our study, two layers are formulated to cope with this problem. Prior to the adoption of command signals, adding logics are included to provide a wash-out of the stick input;_after the signal is adopted, inline control laws will be employed to restrict the aircraft states vary within a reasonable threshold. The latter layer protection strategy is discussed in this paper. The reasonable threshold refers to the flight attitude envelope that stipulates the feasible range of the attitude angle of the aircraft at each altitude._The envelope can be understood within the two stages of flight mission. In landing/take-off cycles, when altitude of the aircraft is low, the envelope keeps the airframe from scratching with the runway. In high altitude stage, the envelope is gradually enlarged as the altitude increases. Therefore the envelope in stage two ensures the passenger-ride quality of the aircraft.

The employed control law is then introduced to structure the attitude protection system. A preliminary control framework is constructed to restrict the Euler angles within the envelope. A two-stage polyline strategy using only classic proportionate/differential feedback is used currently to guarantee engineering-availability of the system. Flight tests of the proposed envelope and control block are conducted on the real-time flight simulation station in Fudan University. The station is constructed based on Matlab/Simulink using the Flightgear toolbox. Turbulence, gust and shear models of the wind are included in the test to represent possible exogenous disturbances. Based on the test maneuver, the control strategy discussed herein is believed to be applicable.

2 Attitude Envelope

The flight envelope is defined as a set of curves consist of flight state points which ensure the aircraft against dangerous situations. The flight control system can warn the pilots when the aircraft is approaching the threshold of the angle of attack, velocity, altitude, and other flight state, according to the envelope. Analogously, an “attitude envelope” imposes a restriction on pitch/rolling angle at each current flight altitude. In principle, the attitude envelope prevents the airframe from interfering with the runway.

The attitude envelope herein is divided into two stages based on the flight altitude. In landing/take-off cycles, when altitude of the aircraft is low, abrupt change of the pitch/rolling angle could induce a scratch with the runway, to the damage of the airframe. A reasonable attitude envelope should not only protect the objective aircraft from scratching with the runway, but also reserve the maneuverability of the aircraft as far as possible. If we briefly take only tail and wingtips into account to frame the envelope, other components would potentially get wounded. On the other hand, if the attitude constraint is too tight in order to avoid the impact, the aircraft will lose its maneuverability, which could lead to worse situations for the aircraft cannot adequately turn off to evade the barriers. Hence the envelope for ground-proximity stage should be elaborately designed.

The tailor-made envelope based on the detailed geometrical data of the objective airframe accomplishes the requirements appropriately. It fits the airframe precisely so that the envelope can protect the aircraft from scratching with the runway while barely peculate the maneuverability. The height of the point on the airframe at certain attitude angle can be calculated by equation 1. Wherein h_m refers to the height of the center of mass in earth coordinate [4]. We should notice that the z-axis directs to earth. To prevent the objective aircraft from interfering with the runway, the lowest point of the airframe must have a positive altitude.

$$h_* = h_m - z_g = h_m - [-\sin\theta \quad \sin\phi\cos\theta \quad \cos\phi\cos\theta][x_b \quad y_b \quad z_b]^T \tag{1}$$

It is computationally intractable to traverse all the points on the airframe. According to the shape characteristics, specific components of the airframe have greater potential to interfere with the runway. For the aircraft discussed herein, 11 representative points on the aircraft including nose, wing tip, tail, and other components are included. Most of the selected components are on the underside of the aircraft, and close to the edge of the airframe. The coordinate positions of the 11 points in body axis are listed in Table 1.

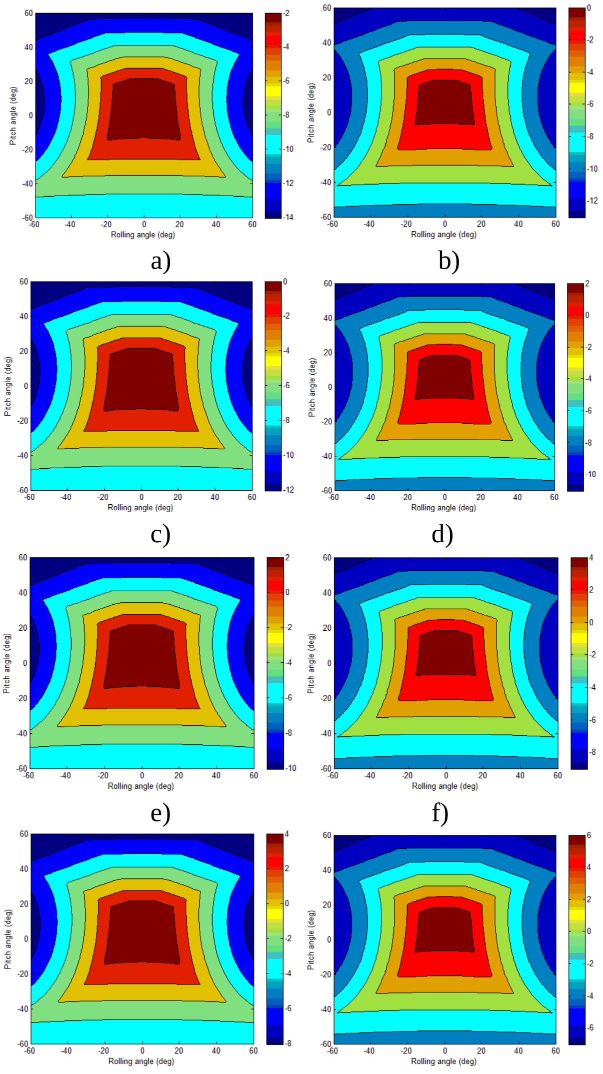
Table 1. Positions of the Components in Body Coordinate

Attention points	X_b (m)	Y_b (m)	Z_b (m)
Tail	-19.48	0	-2.070
Nose	14.697	0	0.920
Nose frame	12.512	0	1.610
Wingtips	-2.185	± 18.975	-0.805
Tailplane tips	-17.480	± 6.095	-2.070
Belly	-5.819	0	2.070
Nose gear	9.062	0	3.220
Main gear	-1.380	± 2.415	3.220

All the 11 points must have a positive altitude, videlicet, all elements value of the h_* vector in equation 1 must be greater than zero to prevent the objective aircraft from interfering with the runway. Although the scope of the safe Euler angles can be obtained directly by solving the multidimensional inequalities, it is too cumbersome to implement the calculation.

To simplify the problem, we reversed the known and unknown conditions. At each flight altitude, we calculated the altitudes of the selected points at each Euler angle. Then we marked and picked out the numerical value of the Euler angle where the height of the lowest point equaled to zero. The picked out Euler angle value composed the scope of the safe attitude angles at the current flight altitude, namely, the rudiment of the attitude envelope.

Eight integer flight altitudes, from ground to seven meters high, were selected as the default condition to be calculated. The ranges of the Euler angles were set from -60 degrees to 60 degrees for both pitch and rolling angle. The contour maps of the lowest point at each flight altitude are shown in Figure 1. We picked out and stacked up the boundary of the safe Euler angles of the default flight altitudes in Figure 2. So far we have obtained the theoretical attitude envelope, which can keep the aircraft from the impact threat. However, it is not considerate enough for the civil aircraft specifically. For the attitude restriction at the flight altitude higher than seven meters, the attitude envelope keeps the same size to ensure the passenger-ride quality. The integrate attitude envelope is displayed in Figure 3.



a) b)

c) d)

e) f)

g) h)

Fig. 1. Contour Maps of the Lowest Points of Objective Aircraft. In subfigure a) to h) the flight altitude increases from 0m to 7m with an interval of 1m.

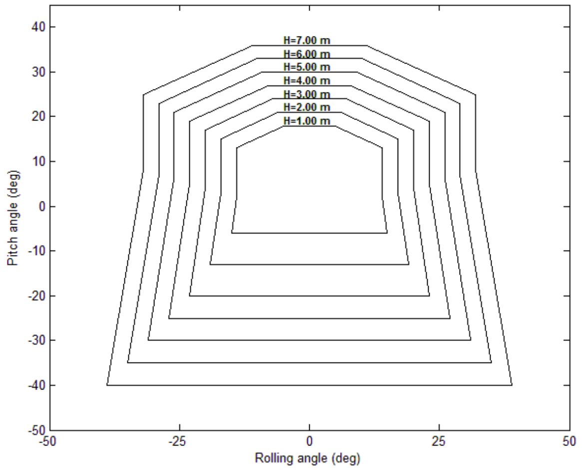


Fig. 2. The Theoretical Attitude Envelope of Objective Aircraft.

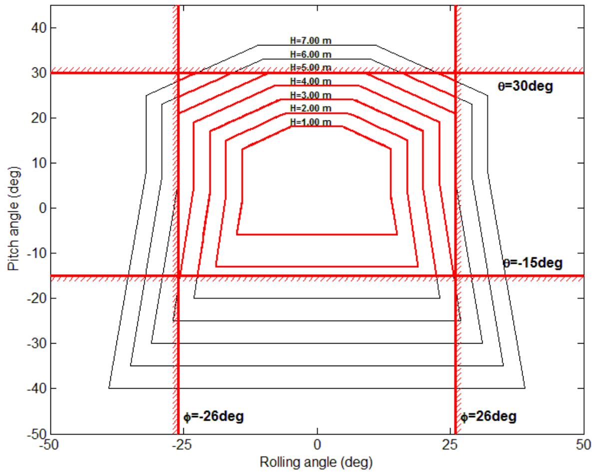
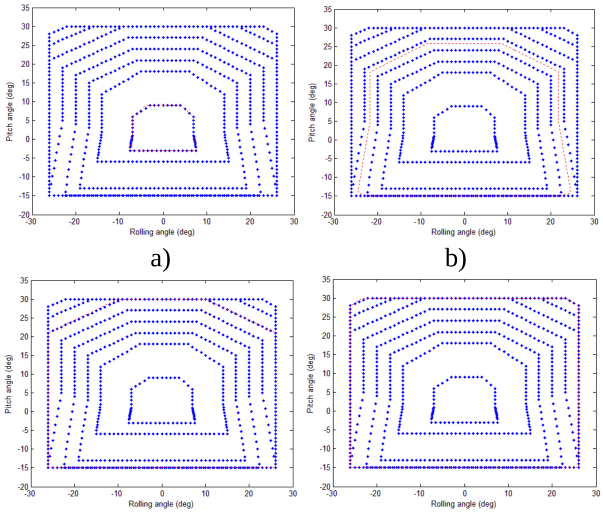


Fig. 3. The Integrate Attitude Envelope of Objective Aircraft.

Based on the attitude envelopes at the selected altitudes, the applicable real-time attitude envelope can be acquired by using linear interpolation method. Example results at four typical altitudes are displayed in Figure 4. Compared with the theoretical attitude envelope, there is an amendment adopted in the real-time attitude envelope. As long as most of the aircrafts do not land horizontally, we set the attitude restriction free if the flight altitude is lower than 0.5 meters.



a) b)

c) d)

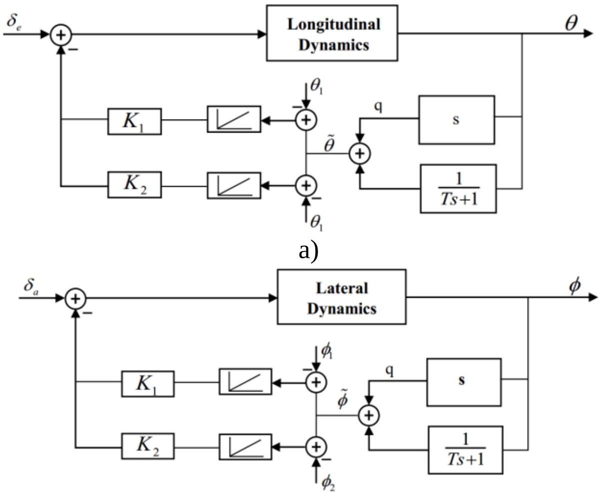
Fig. 4. The Real-time Attitude Envelope of Objective Aircraft. a) The altitude is less than 0.5m. b) The altitude is between 3m and 5m. c) The altitude is equal to 5m. d) The altitude is larger than 7m.

3 Control Law of the Attitude Protection

With the rapid development of the active control technology, the stall/load-factor protection system has been applied in civil aircraft popularly. For instance, typical airliners such as A320 series and B777 series are all equipped with mature protection system, which escorts the aircraft to fly safely. The design of AOA (angle of attack) boundary limiter went through the stages from hard limit to soft limit. Early editions of F-8C plane adopted hard limit mode, then survival control system of F-4 equipped the single-stage polyline limit mode, and the AOA limiter of F -16 used two-stage polyline restriction scheme [5, 6]. Whereas researches specific to attitude protection control were rarely published. We thought the attitude protection shared many similar ideas with the AOA boundary limiter, but the slight modification may solve a thorny problem. The restriction of Euler angles can prevent the aircraft from interfering with the runway so as to protect the aircraft and passengers' life.

A preliminary control framework is constructed to protect the aircraft state within the attitude envelope. Currently, to guarantee engineering-availability of the system, a hard-limit concept using only classic proportionate/ differential feedback is used.

Control blocks are shown in Figure 5, and the parameters are listed in Table 2. The two-stage polyline restriction scheme based on the original scheme applied in the AOA restriction control in F-16 fighter is adopted [7].



a)

b)

Fig. 5. The Control Framework of the Attitude Angle Limiter. a) The pitch angle restriction control framework. b) The rolling angle restriction control framework.

Table 2. Parameters of the Control Framework

	θ_1	θ_2	ϕ_1	ϕ_2	T(s)
Positive angle	$0.6\theta_{\max}$	$0.8\theta_{\max}$	$0.6\phi_{\max}$	$0.8\phi_{\max}$	0.02
Negative angle	$0.6\theta_{\min}$	$0.8\theta_{\min}$	$0.6\phi_{\min}$	$0.8\phi_{\min}$	0.02

Figure 5 (a) illustrates the pitch angle control scheme. If $\tilde{\theta}$ is less than θ_1, the feedback loops remain in standby state. The output responses keep the same as the open-loop system. If $\tilde{\theta}$ increases between θ_1 and θ_2, then the first loop switches to operating state, the close-loop gain is in action to restrict the pitch angle response. If theta tilde is larger than θ_2, then both loops are connected to restrict the close-loop response harder. Figure 5 (b) illustrates the rolling angle control scheme. The control strategy is similar to the pitch angle control scheme.

To serve different flight situations, the feedback gain changes according to the flight state to ensure the aircraft keep inside the attitude envelope and to make the feasible range of attitude angle to the limit of the envelope as close as possible. The value of the feedback gain coefficients are scheduled based on the following criteria. The attitude envelope changes its size according to the flight altitude; and the output response value changes based on the magnitude of input data. The adaptive gain coefficients guarantee the extreme value of responses fitting the envelope boundary but not being overflowed.

The signal $\tilde{\theta}$ is the combination of the pitch rate and the pitch angle data through the low pass filter. The filter allows an access to the signal frequency below 50Hz. The thresholds to activate the feedback loops are set as 60% and 80% of the pitch/rolling angle limit. For the classic proportionate feedback strategy is unable to avoid the overshoot response, the second stage threshold should keep a certain distance from the boundary. The same is true to the rolling angle restriction.

4 Flight Simulation Test

Flight test of the proposed envelope and control block is conducted on the real-time flight simulation station as in Figure 6. The station is constructed based on Matlab/Simulink using the Flightgear toolbox. The framework of the attitude protection simulation structure is shown in Figure 7, which illustrates the signal flow in the simulation station.

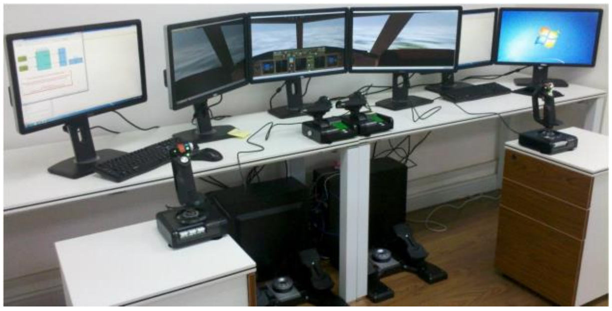


Fig. 6. The Real-time Aircraft Simulation Station

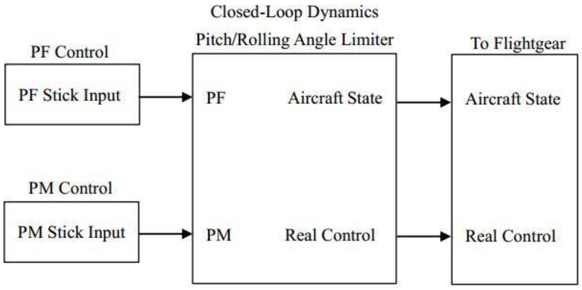


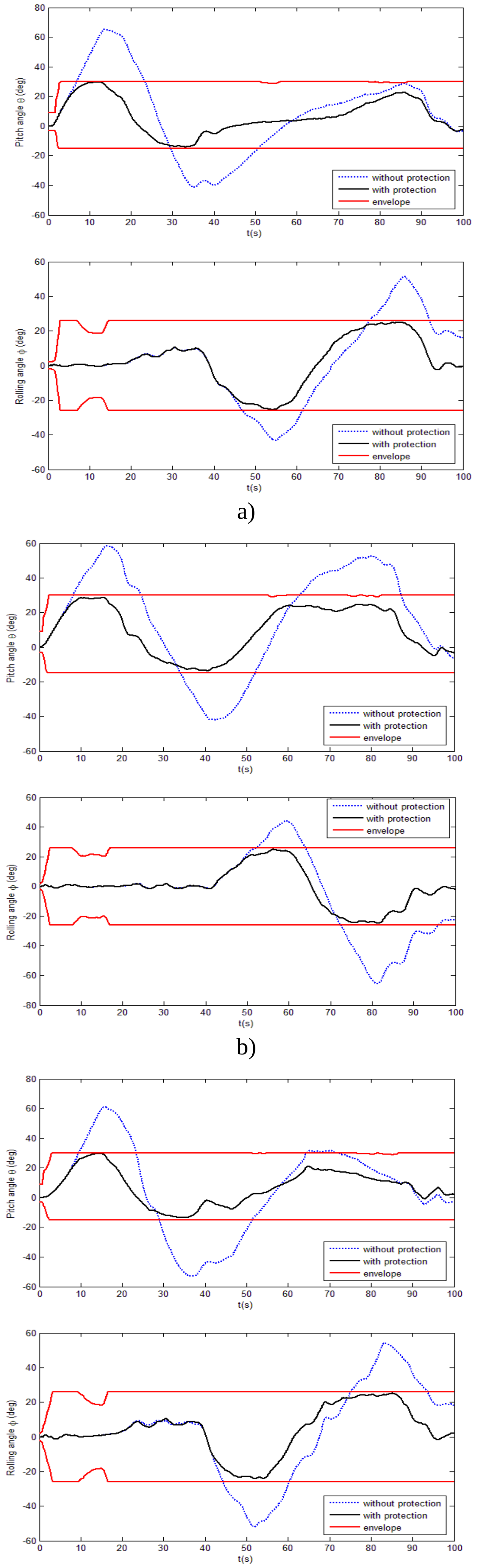
Fig. 7. The Signal Flow of the Attitude Protection Simulation Structure.

Turbulence, gust and shear model of wind are included in the test to represent possible exogenous disturbances. The Dryden Turbulence Model, Discrete Wind Gust Model and Wind Shear Model embedded in Simulink are adopted to generate the disturbance winds. Flight tests were taken under the condition listed in Table 3. The aeroblk_HL20 demo model embedded in Matlab is taken as the reference to set the wind condition parameters. Test results are shown in Figure 8. The black solid line refers to the real-time response of the close-loop system (with protection). And the blue dot line refers to the off-line simulation response of the open-loop system (without protection). The red lines in the figure represent the limit of pitch/rolling angles stipulated by the attitude envelope.

The simulation starts at 0.3 meters high, so that the envelope remains the same size until the flight altitude is higher than 0.5 meters. Then the envelope enlarges as the altitude increases. As the flight altitude rises over seven meters, the envelope remains in constant size. The crinkles afterwards refer to the bevels of the envelope shown in Figure 3.During the flight tests, the pilot of flight (PF) operates the flight normally, while the pilot of monitor (PM) deliberately operates the flight to make the superposition of the input signal, which leads the open-loop response overshoot the attitude threshold. Figure 8 indicates an interference of the envelope could happen if the system is without protection. However, close-loop response of the system yields a safe flight well within the envelope. Based on the test maneuver, the control strategy discussed herein is believed to be applicable.

Table 3. The Wind Condition in Flight Test

Test number	Wind speed at 6m altitude (m/s)	Gust amplitude (m/s)
1	5	[3.5 3.5 3.0]
2	10	[3.5 3.5 3.0]
3	10	[7.0 7.0 6.0]



a)

b)

c)

Fig. 8. The Aircraft Response of the Test Maneuver

5 Conclusion

Generally, civil aviation aircrafts have a long fuselage and wide wings, a tiny shift of pitch or rolling angle would generate a large displacement of the wingtip, tail or other components, which could lead to impact accidents during taking off or landing stages. The attitude envelope is therefore designed to avoid the aircraft scratching with the runway. The attitude envelope herein divided into two stages based on the flight altitude. The envelope for ground-proximity stage protect the aircraft from impact accidents. As the flight altitude higher than seven meters, the attitude envelope keeps the attitude restriction to ensure the passenger-ride quality. Besides, the control law based on the two-stage polyline restriction scheme is developed to organize the attitude protection control system. Based on the simulation flight test results, the response of the close-loop system performs a safe flight well within the attitude envelope with attitude protection. Moreover, the attitude protection system can protect the aircraft both in calm wind and exogenous disturbance in certain circumstance.

In future work the authors plan to examine robustness of the proposed control framework, In addition, an overall test in conjunction with the stick adding logics will be conducted. Furthermore, distribution of superiority between human pilots and control laws also warrants the authors’ very close attention, as the control work presented herein is formulated to washing out manual control from the pilots.

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