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# Research on automatic landing control for the Jumbo Jet

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**Abstract**

This work mainly focuses on automatic landing control methods for the jumbo jet. The six degree-of-freedom nonlinear model of Boeing707 has been established, using classical control method, gliding beam guidance law, lateral beam guidance law, autoflare guidance law and lateral deviation control law have been designed respectively, at the same time, the control flame of automatic landing system has been presented. Through designing inertial delay desalination device, smooth mode conversion has been achieved. Three-dimensional simulation of the whole automatic landing control process indicetes, the designed control system can meet the requirements of performance index, and achieve accurate attitude and trajectory control, so it can guarantee safety and comfort of automatic landing process.

**Keywords** - Beam Riding, Auto-flare, Mode Conversion, Classical Control, Three-dimensional Simulation.

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## I. INTRODUCTION

Landing process is a complex phase that accidents often happen, for this phase, guaranteeing flight safety and comfort is more important, and it puts forward higher requirements on accuracy of control system. So far, there are three kinds of landing guidance methods, they are instrument landing system（*ILS*）, microwave landing system（*MLS*） and global positioning system （*GPS*）. Among these, technology of *ILS* is relatively more mature, and it's one of the available schemes of our large passenger aircraft's automatic landing system developing. Generally, *ILS* includes three subsystem, they are gliding beam guidance system, lateral beam guidance system and auto-flare system. The whole landing process can be divided into five stages, altitude-positioning flight, altitude capture, gliding, auto-flare and landing run. Figure 1 shows the whole landing process. At first, altitude-positioning flight program is carried out when the altitude is 500m, then at this altitude, gliding beam is captured. After the aircraft entered into gliding window, gliding program is carried out. As the beam guidance system will diverge when the aircraft is close to the ground, so beam guidance system must be cut off when the altitude is 45m.The aircraft continues to glide with current attitude until the altitude is 15m. At last, the auto-flare program is carried out, the altitude decreases according to exponential form, and makes the aircraft land with allowable vertical velocity and altitude.

So far, domestic references about automatic landing control for the jumbo jet are relatively few compared with *UAV*, and very few references both at home and abroad do research and simulation on three-dimensional simulation of automatic landing control methods. Ref. [1] used discrete quantitative feedback theory to design auto-land controller, and they provided superior performance robustness of *PI* controller, but they didn't simulate the whole landing process. Ref. [2] used nonlinear energy-based control method (*NEM*) to design automatic landing control law for a twin-engine civil aircraft. In this paper, by modifying the energy functions, stabilization and tracking function can be achieved. Ref. [3] discussed application of multiobjective optimization and designed automatic-landing control law for a civil aircraft, but only longitudinal controllers were designed. Ref. [4] devised a new nonlinear control law in the pitch axis, and all controllers showed robustness against modeling deficiencies or any disturbance due to turbulence or gust wind. Ref. [5] used feedback linearization method to design automatic landing controller, this method can guarantee good tracking performance respect to a given glide-slope trajectory, but they only used three degree of freedom nonlinear aircraft model. Ref. [6] used *INS- /ILS/RA* integrated navigation method to improve dynamic quality of beam error control system, and reduce noise effect, but they only gave simulation

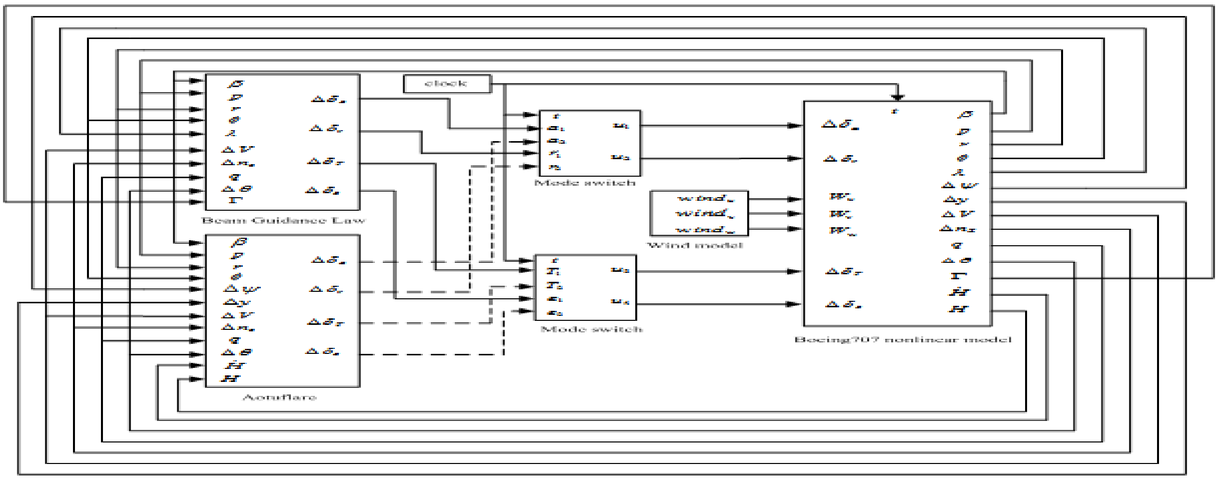

Figure 3. Automatic landing control system structure chart

Figure 3. Automatic landing control system structure chart

Results of beam error angle and altitude error. Ref. [7] presented an auto-landing controller via adaptive backstepping method, and the controller was able to effectively guide *UAV* along the flight path command under wind turbulence. Ref. [8] designed Fuzzy-*PID* controller for automatic landing system, but there is only simulation of longitude channel.Our work focuses on research of control law design method and three-dimensional simulation of the whole landing process, as classical control method has been widely used in engineering field, this work has certain reference value for the development of the jumbo jet.

## II. MODELING AND CONTROL REQUIREMENTS

Used data of Boeing707, the six degree of freedom nonlinear model can be established, as Fig. 2 shown. With assumed conditions of plane earth model, using European and American coordinate system and S-function of Matlab, the nonlinear model is established. In Fig. 2, $\Gamma$ is gliding beam angle, it is satisfied with (1), (2) and (3). Among these, $R$ is distance from projection of aircraft's gravity center to standard gliding line to the radio beacon station. And $d$ is distance from gravity center to standard gliding line.

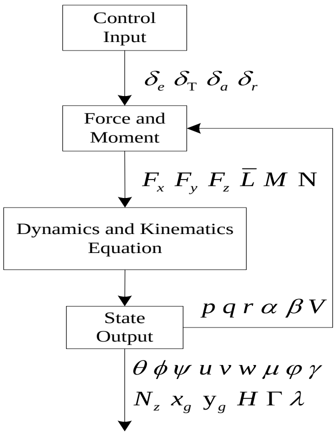

Figure 2. Mathematical model structure chart

$$\dot{d} = V\sin\left(2.5^\circ + \mu\right) \tag{1}$$

$$\tan\left(\Gamma\right) = d / R \tag{2}$$

$$R^2 + d^2 = \left(H / \sin\left(\mu\right)\right)^2 \tag{3}$$

$\lambda$ is lateral beam error angle that deviated from standard gliding line, it can be expressed as (4) and (5).

$$\dot{y}_g = -V\sin(\varphi - \psi) \qquad (4)$$

$$\lambda = \sin^{-1}(y_g / R) \qquad (5)$$

## III. Linear Model

For using linear method to design control law, the linear model must be got. Using trim command of Matlab, the trim point can be solved, then using linmod command, and linearization can be handled based on small disturbance theory around the trim point. Through neglecting coupling between longitudinal channel and lateral channel, linear state-space equation of each channel can be got. According to the landing process shown in Fig. 1, four trim points can be selected to simulate the landing process, Table 1 showed the four trim point of landing phase.

Table 1. Four trim point

| State Variable | State 1 | State 2 | State 3 | State 4 |
|---|---|---|---|---|
| Altitude | 500m | 500m | 300m | 0m |
| Airspeed | 80m/s | 80m/s | 80m/s | 80m/s |
| Track bank angle | -3deg | 0deg | -2.5deg | -2.5deg |

Four state variables are selected to represent longitudinal motion of *Boeing*707, that is, $x = [\Delta V \quad \Delta\alpha \quad \Delta q \quad \Delta\theta]^T$. The corresponding control variable is $u = [\Delta\delta_e \quad \Delta\delta_T]^T$, then longitudinal state-space equation can be shown as （6）, here all the units of angle are rad.

$$\dot{x} = A_{lon}x + B_{lon}u \qquad (6)$$

Lateral state-space equation can be shown as （7）.

$$\dot{x} = A_{lat}x + B_{lat}u \qquad (7)$$

In （7）, State variable is $x = [\beta \quad p \quad r \quad \phi]^T$, control variable is $u = [\delta_a \quad \delta_r]^T$.

⑵Control Requirements

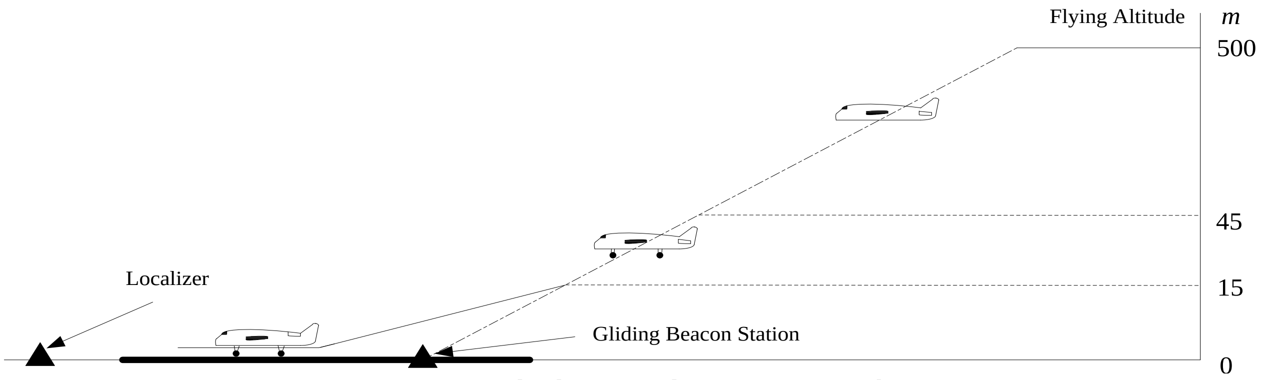

Figure 3. Automatic landing control system structure chart

**Figure 1. Landing process diagram**

The requirements of civil aircraft's automatic landing control system design are very strict. For most civil aircraft, the approach speed is $70$□$85$ m/s, at this time, as track bank angle is $-2.5°$□$-3°$, vertical velocity is $-3.5$□$-4.5$ m/s. However, such big velocity is not allowed when the aircraft is closed to the ground, vertical velocity closed to the ground should be within the limits of $-0.3$□$-0.6$ m/s. In consideration of landing safety, when the aircraft is close to the ground, pitch angle should keep $1°$. At the same time, fuselage must be directed at runway center line, and make roll attitude remain at zero degrees.Indentations and Equations

## IV. CONTROL SYSTEM DESIGN

In this section, gliding beam guidance law, lateral beam guidance law, auto-flare guidance law and desalination device control law will be designed. The structure of the whole automatic landing control system is shown as Fig. 3. In Fig. 3, six degree of freedom nonlinear model is located in “Boeing707 Model” module. “Beam Guidance” module includes beam guidance law, “Leveling” module includes auto-flare guidance law and lateral deviation control law, “Mode Switch1” and “Mode Switch2” includes desalination device, “Clock” includes clock signal. Using root locus method, control law can be designed according to the order from inner loop to outer loop. Firstly, through neglecting coupling among each channel, the simplified transfer function of each channel can be gotten, and control law design is based on these transfer functions. It is worth pointing out that the designed control law must be verified in nonlinear system at last.

①Automatic landing control law design

In fact, automatic landing control is a kind of trajectory control, and trajectory control’s inner loop is attitude control. Longitudinal pitch control uses $C^*$ scheme and feedback of pitch angle, lateral roll attitude control is achieved by feedback of yaw rate $r$, roll angle $\phi$ and sideslip angle $\beta$.

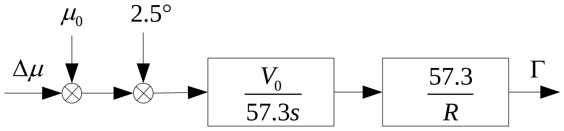

Figure 4. Kinematical link of gliding beam guidance

a） Gliding beam guidance law design

Kinematical formula of Gliding beam guidance is shown in (1), (2) and (3). In order to design PID controller, (1), (2), and (3) can be expressed as a linear form approximately, as shown in Fig. 4. Pitch attitude control loop is the inner loop of gliding beam guidance control loop, and its control structure is shown in Fig. 5. Feedback of gliding beam error angle $\Gamma$ makes the aircraft track the standard gliding line. From (2) we can see, when $\Gamma$ =0, $d$ =0, that is, gravity center of the aircraft is located in the standard gliding line, and flying trajectory coincides with the standard trajectory. For eliminating error, gliding beam coupler uses *PI* control form.

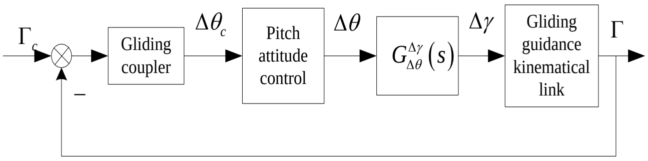

Figure 5. Gliding beam guidance control structure

b） Lateral beam guidance law design

It is the same with gliding beam guidance law design, roll attitude control is the inner loop of lateral beam guidance control, Kinematical formula of lateral beam guidance is shown in (4) and (5), and their approximate linear form is shown in (8).

$$\lambda = -\frac{V\Delta\psi}{Rs} \qquad (8)$$

Using *rltool* command of Matlab, the lateral beam coupler can be designed. Through designing, when the controller has a PD form, response curse of lateral beam error angle is the best. At this time, root locus of the closed lateral beam control loop is shown in Fig. 6, and the damping ratio of dominant pole is 0.484.

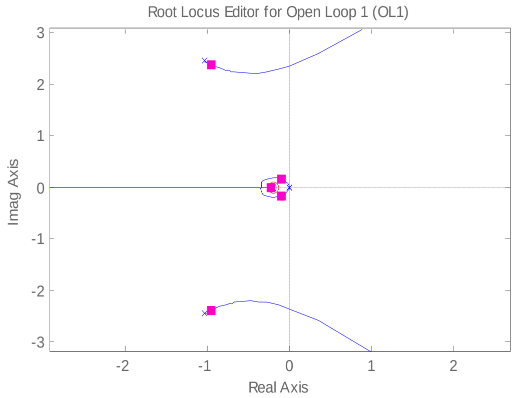

Figure 6. Root locus of lateral beam guidance loop

Beam （gliding beam and lateral beam） guidance law is shown in (9).

$$\begin{cases} \Delta\delta_e = G_s\left(K_1C^* + K_2\left(\Delta\theta_c - \Delta\theta\right) + K_3\int\left(\Delta\theta_c - \Delta\theta\right)dt\right) \\ \Delta\delta_T = G_E\left(K_4\left(\Delta V_c - \Delta V\right) + K_5\dfrac{d\left(\Delta V_c - \Delta V\right)}{dt} + K_6\int\left(\Delta V_c - \Delta V\right)dt\right) \\ \Delta\delta_a = G_s\left(K_7\Delta p + K_8\left(\Delta\phi_c - \Delta\phi\right) + K_9\int\left(\Delta\phi_c - \Delta\phi\right)dt\right) \\ \Delta\delta_r = G_s\left(K_{10}\Delta r + K_{11}\left(\Delta\beta_c - \Delta\beta\right) + K_{12}\int\left(\Delta\beta_c - \Delta\beta\right)dt\right) \end{cases} \quad (9)$$

Among which,

$G_s = \dfrac{-10}{s+10}$ It is ideal steering link,

$G_E = \dfrac{20}{s+20}\dfrac{1}{s+1}$ It is ideal throttle and server link,

$C^* = \Delta N_z + 12.4\Delta p$ It is $C^*$ signal,

$\Delta\theta_c = K_{13}\left(\Delta\Gamma_c - \Delta\Gamma\right) + K_{14}\int\left(\Delta\Gamma_c - \Delta\Gamma\right)dt$ ,

$\Delta\phi_c = K_{15}\left(\Delta\lambda_c - \Delta\lambda\right) + K_{16}\dfrac{d\left(\Delta\lambda_c - \Delta\lambda\right)}{dt}$ ,

$\Delta V_c = \Delta\beta_c = \Delta\Gamma_c = \Delta\lambda_c = 0$ .

c） Auto-flare guidance law design

When the aircraft's altitude is 15m above the ground, auto-flare control system is accessed, and its main task is making vertical velocity decrease to the allowable touchdown velocity. The solution is to make altitude decrease according to the exponential form, with $H$ decreasing, $\dot{H}$ will decrease to the allowable range. Fig. 7 shows control structure of auto-flare system, the difference between gliding beam guidance law and auto-flare guidance law is the form of $\Delta\theta_c$, the selected ideal touchdown speed is -0.2m/s, then $\Delta\theta_c$ in auto-flare guidance law is shown as (10).

$$\Delta\theta_c = \left(K_{17} + \frac{K_{18}}{s}\right)\left(-\frac{H}{5} - 0.2 - \dot{H}\right) \quad (10)$$

Lateral deviation control makes roll attitude control as its inner loop, its form is the same as (9), but $\Delta\phi_c$ in lateral deviation control law is different.

$$\Delta\phi_c = K_{19}\left(\Delta\psi_c - \Delta\psi\right) + K_{20}\int\left(\Delta\psi_c - \Delta\psi\right)dt \quad (11)$$

Among which,

$\Delta\psi_c = K_{21}\dot{y} + K_{22}\left(\Delta y_c - \Delta y\right) + K_{23}\int\left(\Delta y_c - \Delta y\right)dt$ .

②Automatic landing control law design

To simulate the whole landing process, the problem of mode conversion should be solved, so desalination algorithm needs to be researched in this section. The effect of desalination algorithm is to make the cut-off control law secede and make the accessed control law enter gradually. In general, there are three kinds of desalination algorithm, free transform desalination algorithm, “warm backup” desalination algorithm, and “synchronous tracking” desalination algorithm. Among these, structure of free transform desalination algorithm is the most simple, it uses inertial delay link to restrain conversion mode, and it is used for the situation that control law variation is not big. Ref. [9] gave detailed description of this algorithm, here, we used nonlinear desalination algorithm, and it is shown in (12). In (12), the initial control law is $u_A$, From $t_0$ to $t_1$, control laws are switching, after $t_1$, mode conversion process is completed. Parameter $a$ is the main factor of affecting desalination performance, the bigger its value is, the faster conversion rate is.

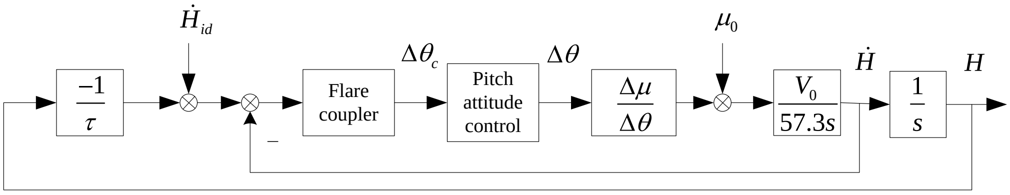

Figure 7. Auto-flare control structure

$$u(t)=\begin{cases} u_A(t) & t\le t_0 \\ u_A(t)e^{-a(t-t_0)}+u_B(t)(1-e^{-a(t-t_0)}) & t_0<t\le t_1 \\ u_B(t) & t>t_1 \end{cases} \quad (12)$$

## V. SIMULATION STUDY

This paper neglects altitude-positioning flight process, initial conditions of simulation are as follows, altitude is 500m, track bank angle is $-3°$. At the beginning, beam signal is captured, initial gliding beam angle error is $0.1°$, initial lateral beam angle error is $0.25°$. When altitude is 45m, beam guidance system is cut off, then, the aircraft continues to glide with current attitude. When altitude is 15m, auto-flare system is access, nonlinear simulation results are shown from Fig. 8 to Fig. 16.

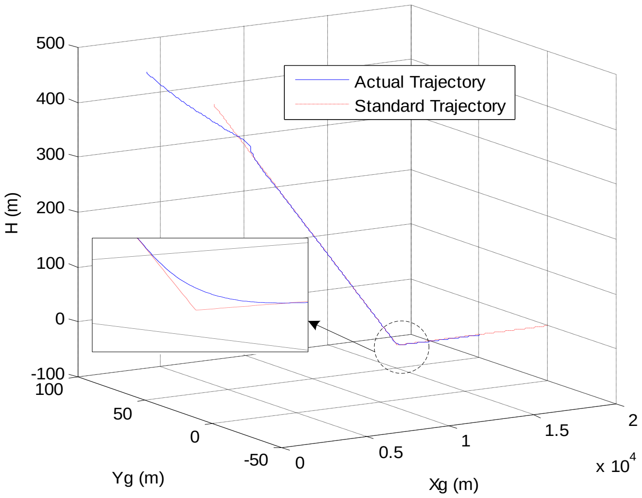

Figure 8. Flying trajectory simulation results

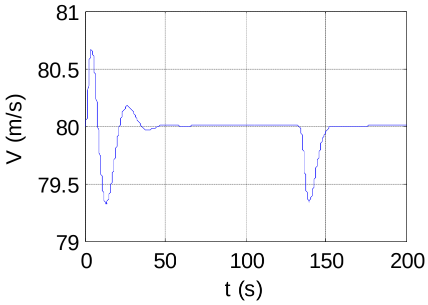

Figure 9. Airspeed response

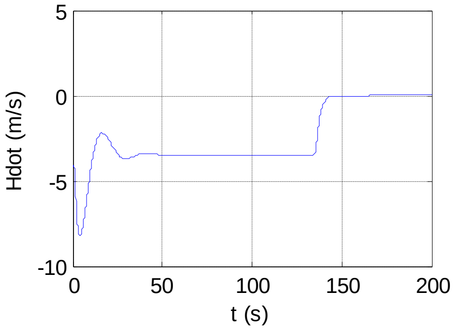

Figure 10. Vertical velocity response

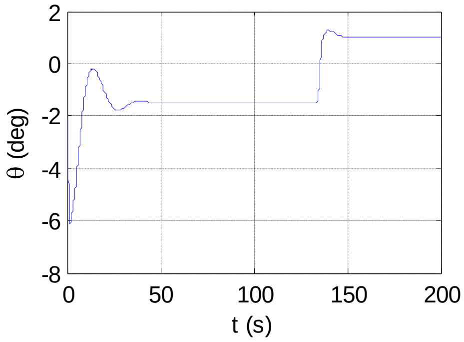

Figure 11. Pitch angle response

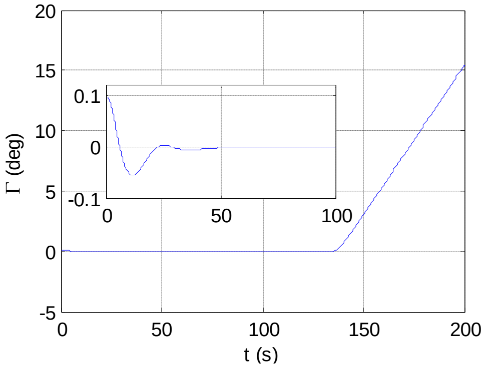

Figure 12. Longitude beam angle response

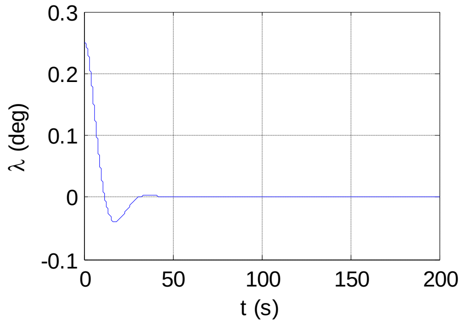

Figure 13. Lateral beam angle response

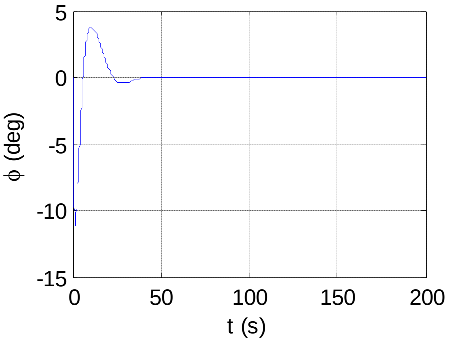

Figure 14. Roll angle response

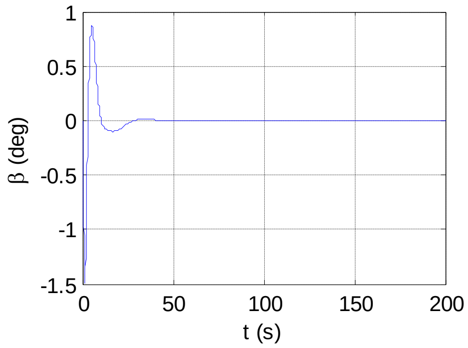

Figure 15. Sideslip angle response

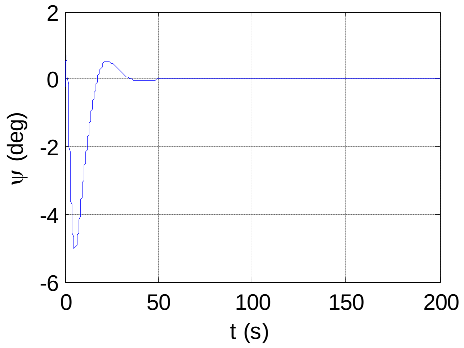

Figure 16. Yaw angle response

From Fig. 8 to Fig. 16 we can see, the actual trajectory can track standard trajectory well, there is no lateral deviation error, altitude decreases according to exponential form when auto-flare system is switched on. In the whole process, airspeed $V$ keeps 80m/s, its biggest change value is within 1m/s. Touchdown vertical velocity is about -0.3m/s which can meet the designing requirements. When the aircraft is gliding, pitch angle $\theta$ is about $-2^\circ$, and when it is closed to the ground, pitch angle keeps $1^\circ$. Lateral beam error angle $\Gamma$ recovers to $0^\circ$ from initial value $0.1^\circ$ after 25s, when aircraft lands on the ground, $\Gamma$ has a phenomenon of emanating, it is because of $R$ tending to 0, and this is the general rule of guidance system. Lateral beam error angle recovers to $0^\circ$ from initial value $0.25^\circ$ after 30s. In landing phase, roll angle $\phi$ and sideslip angle $\beta$ keep $0^\circ$, the maximum value of sideslip angle is $1.5^\circ$. When the aircraft lands on the ground, yaw angle $\psi$ keeps $0^\circ$, it indicates fuselage is directed at centerline of runway. Simulation results indicate that the designed control laws can meet the requirements of performance index, and track the standard trajectory well.

## VI. CONCLUSION

This paper established nonlinear model of Boeing707, designed gliding beam guidance law, lateral beam guidance law, and auto-flare guidance law, and used inertial delay desalination algorithm to achieve smooth switching of flight mode. Three-dimensional simulation indicated, the designed control laws achieved accurate attitude and trajectory control for landing phase, and met the requirements of performance index. As technologies of ILS and PID control method are mature, and their engineering application is comprehensive, in the course of our jumbo jet's development, they can be optional schemes, so our work has a certain research value.

## VII. ACKNOWLEDGEMENTS

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